Master Thesis

Energy Harvesting for Passive Smart Devices

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Abstract

Passive Radio Frequency Identification (RFID) deals with the transmission of energy and information from a reader device to a RFID tag and vice versa. The tag generates the energy for its own operation from the electromagnetic field that is generated by an RFID reader.

The work presents solutions how to use electrical energy, which is generated in parallel to the energy used for RFID Integrated Circuit (IC) operation, for the purpose of driving an external electronic subsystem that allows interaction with the environment.

Within this work different energy harvesting sources are analyzed to supply electronic systems. Special focus is taken on UHF Radio Frequency (RF) harvesting.

An RFID IC which has a second antenna port was used to harvest electrical energy from the RF field. The IC includes a circuitry that converts the RF power into Direct Current (DC). The other major components of a passive smart device are a communication unit, a microcontroller, used for data processing, a power management unit and a charge storage device, such as a capacitance or a rechargeable battery, used as energy buffer.

All these components required for a smart device are analyzed, focusing on concepts to improve energy efficiency during energy harvesting and consumption as well as the design and realization of a prototype.

The prototype developed operates only with power received from the RF field. This smart device includes a Real Time Clock (RTC) and a sensor that allows monitoring the temperature over several days. These readings from the temperature sensor are stored in the RFID IC's memory. A RFID reader device can download this data at any time wirelessly.

Kurzfassung

Passive Radio Frequency Identification (RFID) beschäftigt sich mit der Übertragung von Energie und Information von einem Lesegerät zu einem RFID Transponder und umgekehrt. Der Transponder generiert die Energie für die eigenen Funktionen aus einem elektromagnetischen Feld, das durch ein RFID Lesegerät erzeugt wird.

Die Diplomarbeit präsentiert Lösungsansätze um die elektrische Energie, die parallel zur Energie für den Integrierten Schaltkreis des RFID Transponders erzeugt wird, effizient zu nutzen. Das Ziel ist es mit dieser Energie ein externes elektronisches Subsystem zu betreiben und eine Interaktion mit der Umgebung/Umwelt zu ermöglichen.

Des Weiteren beschäftigt sich diese Arbeit mit der Nutzung unterschiedlicher Energiequellen für das sogenannte „Energy Harvesting". Das Hauptaugenmerk wird jedoch dem Sammeln von Energie aus Ultra-Hochfrequenten Elektromagnetischen Feldern gewidmet.

Ein RFID-IC mit einem zweiten Antenneneingang wird verwendet, um Energie aus dem Elektromagnetischen Feld zu sammeln. Dieser Integrierte Schaltkreis besitzt die Fähigkeit Gleichstrom aus dem Elektromagnetischen Feld zu erzeugen.

Die weiteren Hauptbestandteile eines passiven „Smart Device" sind eine Kommunikationseinheit, ein Mikrokontroller für die Datenverarbeitung, eine „Power Management Unit", sowie ein elektrischer Energiespeicher, wie z.B. ein Kondensator oder ein Akkumulator, der zum Zwischenspeichern von Energie verwendet wird. All diese Komponenten eines „Smart Device" werden näher beschrieben und analysiert. Hierbei wird der Fokus auf Konzepte gelegt, die eine Verbesserung der Effizienz während des Energiesammelns und Verbrauchens versprechen. Zusätzlich wird auf das Design und die Umsetzung eines Prototypen eingegangen.

Der entwickelte Prototyp kann gänzlich mit der Energie aus dem Elektromagnetischen Feld versorgt und betrieben werden. Dieses „Smart Device" beinhaltet eine Echtzeituhr sowie einen Temperatursensor, der über mehrere Tage den Temperaturverlauf aufzeichnen kann. Diese Messwerte werden im Speicher des RFID Transponders abgelegt, von wo aus sie jederzeit drahtlos mit einem RFID Lesegerät drahtlos ausgelesen werden können.

Contents

Abbreviations

µC	Microcontroller
ASIC	Application Specific Integrated Circuit
BAP	Battery-assisted Passive (RFID)
CMOS	Complementary Metal-Oxide Semiconductor
DC	Direct Current
EH	Energy Harvesting
EHD	Energy Harvesting Device
EIRP	Equivalent Isotropic Radiated Power
EM	Electro Magnetic
EPC	Electronic Product Code
ERP	Effective radiated power
ESR	Equivalent Series Resistance
FCC	Federal Communications Commission
FHSS	Frequency-Hopping Spread Spectrum
FRAM	Ferroelectric Random Access Memory
HF	High Frequency (3MHz – 30MHz)
I^2C	Inter-Integrated Circuit, is a serial multi-master bus invented by Philips
IC	Integrated Circuit
ISM	Industrial, Scientific and Medical Band (Frequency Range)
ISO	International Organization for Standardization
LBT	Listen Before Talk
LCD	Liquid Crystal Display
LSB	Least Significant Bit
MCU	Microcontroller Unit
MEC	Micro Energy Cell
MEH	Micro Energy Harvesting
MEMS	Micro-electromechanical systems
MSB	Most Significant Bit
PC	Personal Computer
PCB	Printed-Circuit Board
PMU	Power Management Unit
POR	Power-On Reset
RAM	Random Access Memory
RF	Radio Frequency
RFID	Radio Frequency Identification
RFU	Reserved For Future Use
RTC	Real Time Clock
SCL	Serial Clock Line (I^2C Bus Interface)
SDA	Serial Data Line (I^2C Bus Interface)
SMD	Surface Mount Device
SPI	Serial Peripheral Interface
SRAM	Static Random Access Memory
Tag	Transponder (RFID)
UHF	Ultra High Frequency (300MHz – 3GHz)

Definitions

Source Meter

A Source Meter is a multifunctional electronic lab device which fulfills two main functions:

1. Digital controlled electronic power supply with a regulated voltage, current or power source.
2. Digital Multi-Meter

List of Symbols

Unless otherwise defined.

$t \ldots time$
$f \ldots frequency$
$V \ldots electrical\ Voltage$
$I \ldots electrical\ Current$
$P \ldots electrical\ Power$
$E \ldots electrical\ Energy$
$C \ldots capacitance$
$L \ldots inductance$

1. Introduction

Ubiquitous and pervasive computing becomes more and more important. It is not only focused on handheld and mobile devices like mobile phones, notebooks and tablet PCs. Devices and applications that combine the physical with the digital world or applications that let both worlds interact with each other are of great interest.

It has been proven that wireless communication systems are very flexible to use. Nowadays it is often easier and cheaper to use wireless communication equipment instead of hardwired cables. Nevertheless there is a catch when dealing with wireless equipment. Today nearly every wireless device requires a battery or a power supply that has to be connected to the mains, at least sometimes. Therefore all these devices are not truly wireless devices respectively they are only wireless if they run from battery. All these devices still require cables to get the needed energy for operation.

The central topic of this work is how devices can be made really wireless. Not only wireless concerning communication but also wirelessly powered. Electromagnetic (EM) wireless energy transmission as well as micro energy harvesting techniques are treated in this work.

RFID is an important topic in many operating areas especially in logistics. However for today's applications not only the identification aspect of RFID tags is important. Today's RFID tags are also used for authentication, to carry user data and many more.

In the future some RFID tags will also be equipped with sensors and/or interfaces that allow communication (over I^2C, SPI) with other electronic parts on the Printed Circuit Board (PCB). This enables a new big field of applications for RFID tags that offer these features.

Example applications are:

- Temperature, Humidity Logging and Monitoring
- Electronic Shock Detection
- Electronic Shelf Label
- Wireless Firmware Upgrades
- Configuring and Customizing Already Packed Devices

When thinking about the next step it shows very clearly that it is not enough to only power the communication or identification part of an RFID tag. Also additional functional modules, those are built into, or those are externally connected to the RFID's Integrated Circuits (IC) should be supplied from the received energy.

Because the available/harvestable power from the EM waves as well as the power from other ambient resources are very low and not every time available, concepts with energy storages will be required. These technologies are discussed in section 5.1.

But not only storing the electrical energy is important and a topic in this work, also the careful and efficient use of the harvested and the stored energy enables a well performing system. Therefore an efficient power management system is required. Further details are referred in section 5.2.

Also from another perspective energy harvesting is very useful. It is an important topic for wireless sensors and actuators. The reason for this is that most of today's wireless sensors and actuators are powered from batteries. This leads to the fact that they can run out of charge and have to be replaced someday. Therefore the maintenance-free operation of energy harvesting systems is of great benefit.

In conclusion a main focus of this work is given to RFID especially to energy harvesting for semi-passive UHF RFID. However most of the presented topics and techniques are also applicable to inductive coupled RFID systems.

1.1 Definitions

1.1.1 Smart Device

A Smart Device is a physical object with an embedded processing unit, memory and network-binding. Many “Smart Devices” have a user interface or the ability to interact with the physical environment. [1]

Minimal Requirements for Smart Devices:

- Device can process digital information [1]
- Device can communicate with other devices (exchange data) [1]

“Smart” refers to the ability of the device to processes digital information. A Smart Device doesn’t necessarily require its own “intelligence” in the sense of artificial intelligence. It is enough, if the device can process digital information e.g. logic functions.

As mentioned before the device requires the ability to communicate with other devices and systems. It isn’t necessarily required that communication works online (permanent bidirectional connection) but it is at least required that data/information is occasionally exchanged between smart devices.

For the architecture of smart devices it is more important that they interact and communicate with the environment than the scope of functions or the processing power of the device.

Distinction from universal computers:

Less Functionality and Performance

- More functionality and performance than non-digital Objects [1]
- Less functionality and performance than personal computers offer [1]

Context and Interaction

- Smart Devices are characterized by their context awareness and their interaction with the physical environment [1]
- Embedded Smart Devices doesn’t have a direct user interaction [1]
- Interactive Smart Devices offer a more simple user interface than personal computers [1]

1.1.2 Smart Display

A Smart Display or an electronic controlled display is a smart device with the following set of functions. The device offers the opportunity to change the display content remotely on the users request or automatically based on environmental data.

Some examples for smart displays are electronic shelf labels or displays that can show the current temperature in a digital manner. Another option for electronic controlled price tags is that they can automatically change their content if special discounts are available.

Currently electronic shelf labels are used by the food retail chain “Billa”. This Shelf Label can be updated wireless. It is equipped with an e-paper display (lower right at the shelf label in Figure 1: "Billa" Smart Shelf Label). The great advantage of these smart displays is that the information is automatically and wirelessly updated based on price information from the data base.

Figure 1: "Billa" Smart Shelf Label

Figure 2: E-Paper Display Demonstrator from Retronix Technology

Figure 3: Colored E-Paper Display Module form Pervasive Displays, Image Source: [2]

1.1.3 Passive Device

In the context of this work a Passive Device is a device that does not require a source of energy e.g. a power supply or a non-rechargeable battery. However, in this thesis, it does not mean that no energy for the device's operation is required like the definition of [3] does.

For this work it has to be referred to the definition of Klaus Finkenzeller concerning RFID transponders:

"Passive Transponders do not have their own power supply, and therefore all power required for the operation of a passive transponder must be drawn from the (electrical/magnetic) field of the reader." [4]

1.1.4 Energy harvesting

Energy harvesting is the process that captures or collects the available environmental energy and converts it into electrical one. Energy harvesting or sometimes also called power harvesting or energy scavenging allows electronic devices to operate from non-conventional power sources. This makes a battery replacement or the need for wiring obsolete. [5]

In [6] Klaus Dembowski describes that the terminus Micro Energy Harvesting (MEH) should be preferred if dealing with tiny amounts of energy in microelectronic systems. The reason for this is that energy harvesting is also often associated with environmental friendly energy generation. Such systems are for instance wind mills or solar plants that generate power levels in the range of kW to MW.

Micro energy harvesting (MEH) deals with the conversion of ambient energy into usable electrical energy. Typical sources for micro energy harvesting systems are solar, vibration, heat, wind, electromagnetic waves and electrolytic.

Typical micro energy harvesting devices generate power levels from some µW up to hundreds of mW.

The main advantage of these energy self-sufficient systems is that they are maintenance free. No batteries are required which have to be replaced when empty. This is the most important fact why this kind of system is used more often in the industry. Typical energy self-sufficient systems can be found in the field of industry and in building automation products.

To explain why maintenance freeness for wireless sensors and actuators is so important the following example is given.
It is imaginable that the maintenance effort is very high for big buildings with approximately 10000 battery powered electronic radiator thermostats or wireless fire detectors. Assumed that the battery life time of one device is 3 years, this would lead to the situation that in average every day 9 batteries have to be replaced. This is a situation that can't be handled by a janitor alone efficiently.

The difficulty of self-sufficient systems is that it is often not predictable if the power source is available, especially if the device is a mobile one. Also the strength of source is in most cases not predictable. Therefore excellent power management is required to handle these circumstances.

1.1.5 RFID

Passive RFID Tags

Passive RFID Tags do not have their own power supply they get all the power required for their operation from the electromagnetic/magnetic reader field. In comparison to that active transponders have their own power supply (e.g. battery) which delivers the power required for the operation of the transponder system. [4]

There are two common ways to transmit data from the tag to the reader. The first principle is using backscatter for tags based on electromagnetically wave propagation. The second principle is load-modulation used for inductively coupled tags. Both principles make it possible that the energy required for the return link communication (tag to reader) is used from the reader generated field. [4]

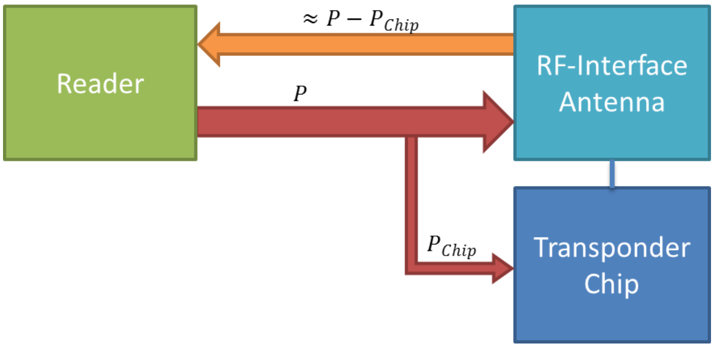


Figure 4: Passive Transponder Topology

The advantage of passive RFID tags compared to active ones is that there is no need of an additional power supply. All required energy for operation as well as for communication is drawn from the reader field. This makes these kinds of transponders very cost effective and maintenance free. Also their lifetime is theoretically infinite because no battery or other components that typically fail over long periods of time are included. The major disadvantage comparing passive powered with active powered tags is the limitation of maximal communication range. Also the processing power and functionality is limited because passive tags have to deal with very tough power constraints.

1.1.6 EPC Global RFID Tag Classification

The industry-driven company EPCglobal Inc., mainly focusing on research related to RFID, defined a class structure for RFID systems focused on UHF or Long Range Systems. The classification describes the differences in functionality from lower class to higher class RFID tags.

Identity Tags (Class 1)

This class describes passively powered tags which uses backscatter or load-modulation for the reverse communication link (tag to reader). A tag in this class has to cover the following features. [7]

- Product code identifier (EPC) [7]
- Tag identifier (TID) [7]

- Kill feature to set a tag to a permanent non-responsive state [7]

Optional features are:

- Recommissioning [7]
- Password protected access [7]
- User memory [7]

Higher Functionality Tags (Class 2)

This kind of tags offers the same features like class 1 defines and requires the following additional features. Also class 2 is understood as passively powered and uses backscatter or load-modulation for the reverse link communication. [7]

- Extended tag identifier (TID) [7]
- Extended user memory [7]
- Authenticated access control [7]
- Additional features that will be defined in class 2 specification [7]

Battery-Assisted Passive Tags (Class 3)

This type of tags is also called semi-passive tags. Tags of this class have the anticipated features of class 2 tags or beyond. Also the tag has a power source to supply itself and/or its sensors and/or actuators, but the tag still communicates passively. This means in the case that the tag has an active transmitter the interrogator has to initiate the communication first. In the other case the interrogator is using backscatter or load-modulation techniques for the reverse link communication. The tag also can have an optional data logging feature. [7]

Active Tags (Class 4)

The main difference to the classes 1-3 is that class 4 tags typically can initiate a communication with an interrogator or with another tag. In some cases the communication protocol may limit the tag to initiate or enable the communication so an interrogator is required to do this. Because these kinds of tags have an autonomous active transmitter, there is the need to have access to a power source like a reader. [7]

Active tags have a full bidirectional radio system with active transmitter and receiver. The transmitter is powered from the tag's power source.

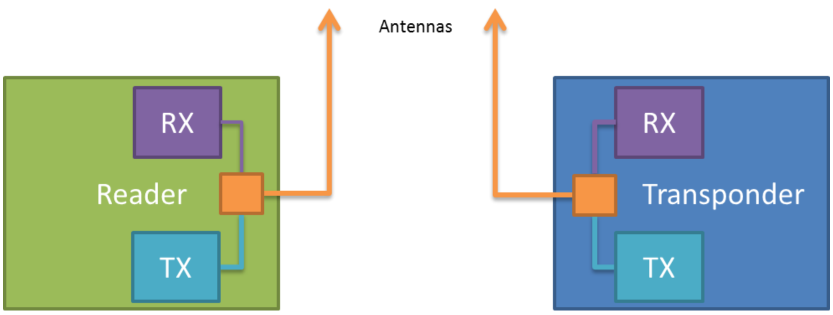


Figure 5: Active Transponder or Radio Device

1.2 Energy Harvesting Principles

1.2.1 Overview

Most of today's wireless sensors that are powered from harvested energy are using solar cells. Thermoelectric converter technology is used less often because the availability in the electromagnetic field is quite low. The only major application area where RF harvesting is used is passive RFID technology.

Typically energy harvesting is used for an application where replacing batteries is not desirable.

Examples for the energy yield, harvestable from different sources:

Energy Source	Characteristics	Efficiency	Harvested Power
Photovoltaic/Light	Outdoor Indoor	≈10-24%	100mW/cm² 100µW/cm²
Thermal Energy	Human Industrial	≈0.1% ≈3%	60µW/cm² ≈1-10mW/cm²
Vibration/Motion	Human (Hz) Machines (kHz)	≈25-50%	≈14µW/cm³ ≈800µW/cm³
RF Waves	GSM 900MHz WiFi	≈50%	0.1µW/cm² 1nW/cm²

Table 1: Typical Harvestable Energy Levels [8]

Generally the biggest difficulty when dealing with energy harvesting transducers is to convert the voltage and current level from the transducers output to usable levels for standard IC's such as microcontroller units.

Also the efficiency is an issue. Therefore Maximum Power Point Tracking (MPPT) is a technique that is often recommended to increase the efficiency for various operating points. If this is too much effort then matching the impedance of source and load for a single point is also an option.

1.2.2 Photovoltaic (Light)

Solar cells are widely used to power the consumer electronic products e.g. pocket calculators. Solar cells are low cost compared to other energy harvesting transducers. Especially in relation to the output power they can deliver. Also the output voltage of solar cells does not necessarily require signal conditioning. Often the power output can be directly used to operate electronic circuits.

Advantages:

- Moderate efficiency
- High ratio between area and power output compared to other energy harvesting technologies

Disadvantages:

- Requires Light (does not work in the night or in the dark)
- Boost converter is recommended to increase the range of operation in difficult light situations

Note: For energy harvesting applications often amorphous (thin film) silicon solar cells are preferred because they offer higher output voltages for dark light conditions.

Example Applications: solar calculator, wireless solar keyboard, wireless temperature sensor

1.2.3 Electrodynamics Transducer (Motion, Force)

Electrodynamics and electromagnetic transducers generate energy based on electromagnetic induction. The law of induction describes generation of an electric field (voltage) in a wire loop by changing the magnetic flux density through it.

This principle is of course used in electric generators to produce the electricity in big scale. There is no need to describe this principle in detail here.

Advantages:

- simple
- inexpensive

Disadvantages:

- moving mechanical parts
- not noiseless

Example Application: This principle is often used for wireless switches. When pressing the switch a permanent magnet is pushed through a coil. This mechanical action generates the energy for transmitting a message that the switch was pressed.

1.2.4 Piezo-Transducer (Mechanical Vibration)

To generate electricity from kinetic piezoelectric transducers can be used. Beside the electrodynamics transducer this is the second most common principle generating energy from kinetic energy. Piezoelectric transducers use the energy from pressure, shock and vibrations from machines or human motion to generate electricity.

Advantages:

- small

Disadvantages:

- High output voltages, low output current
- For efficient use with electronic systems converters are required

Note: Piezoelectric elements offer good power output results if the element vibrates at resonance frequency.

Example Applications: wireless condition monitoring for mechanical machines, tire pressure monitoring.

1.2.5 Thermo electric Generators (Thermal Energy)

A thermo electric generator produces energy out of thermal energy. It converts a temperature difference into an electrical voltage. The higher the temperature difference is the higher is the resulting voltage. The Seebeck effect describes this phenomenon in more detail.

$$V_{Seebeck} = (S_B - S_A) \cdot (T_2 - T_1)$$
$$S \ldots Seebeck\ coefficient$$

The Seebeck coefficient describes the property of the conductors or semiconductors. The bigger the differences between the Seebeck coefficients and the temperatures of those two materials are the higher is the resulting voltage. The Peltier effect describes the opposite of the Seebeck effect, the conversion of electrical energy into a temperature difference.

In a thermo electric generator usually many elements are connected in series to reach higher voltage levels. However in most cases, the reached voltage level is still very low so it requires voltage boosting before it can be used to supply electronic systems.

It is also possible to use the Seebeck effect on semiconductors. Semiconductor technology enables small form factors, high integration density and large differences of the Seebeck coefficients.

The voltage level generated due to the Seebeck effect is very low. Therefore it is necessary to connect multiple elements in series to reach voltage levels that can be converted by DC/ DC converters.

In practice for energy harvesting applications Peltier elements are often used. The difficulty, when dealing with thermo electric generators, is to convert very low voltage levels (>20mV) to voltage levels that are required by the electronic system. This is necessary because in most used cases the temperature difference is only a few degrees.

Advantage:

- amount of power that can be delivered is high compared to other energy harvesting methods (RF, Vibration)
- waste heat of machines and devices can be used to supply sensors
- noiseless

Disadvantages:

- A hot object or climate is not enough. A temperature difference is required. Therefore it cannot be used in closed environments e.g. no airflow, no temperature gradient
- Expensive
- Very low output voltage levels, however high currents
- For moderate output voltages, many elements have to be connected in series as well as a high temperature difference is required

- For efficient use in electronic systems a voltage boost converter is mostly required.

Example Applications: electronic controlled radiator thermostat, wireless temperature monitoring for high current conductor bars.

1.2.6 RF energy harvesting

For generating power out of electro-magnetic RF waves usually dipole antennas are used. Also other antenna designs that offer higher antenna gains are possible, but they are more complicated. Furthermore impedance matching and a resonance circuit with a high quality factor are required to produce applicable electricity from low field strength.
In most cases these RF harvesters are designed to work efficiently only in a small frequency band. Designing an RF harvester for multiple frequency bands or broadband would increase the power output however these designs become more complex.

Advantages:

- Inexpensive
- High integration possible
- RF waves are not directly noticeable by humans

Disadvantages:

- only very low power levels reachable
- mostly not practically useable with the ambient radiation of telecommunication transmitters (to less energy)

Example Applications: passive RFID

Note: widely used passive RFID systems using an active transmitter to supply tags in the closed environment

This section shall not describe RF energy harvesting in detail because Section 2 devotes UHF energy harvesting great attention.

1.2.7 Comparing Energy Harvesting Technologies, Summary

Generally all types of energy harvesting methods rely on the availability of their particular kind of energy source. If the energy source is not available there cannot be any energy output on the electrical side. This causes that most applications require energy storages to overcome outages of the energy source.

The main disadvantage in general is that most energy converters require an adaption circuit to transform the produced voltage and current to the required values.

Comparing the presented technologies it is apparent that solar cells are the way to go, if the amount of power output counts. Nevertheless each technology has its advantages for its particular use case.

1.3 Energy Harvesting System Architectures

Figure 6 shows the simplest architecture of an energy harvesting system. This system has no energy storage. Electrical energy output is only available if energy can be generated out of the environment. Typically this architecture is used for systems that do not require permanent power supply, for instance passive RFID tags and wireless switches for home automation. In the case of passive RFID tags the RF field has to be applied to before a command can be sent to the tag. The wireless switch is powered from the energy generated during the push action. After transmitting the event message it runs out of energy. Nothing more is required for this application.
The advantage of this architecture is that it is very simple and inexpensive.

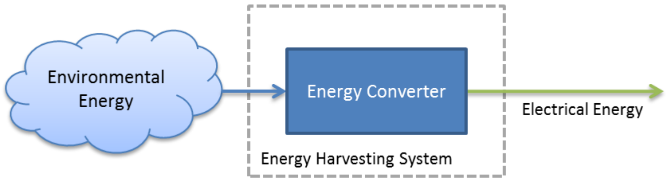


Figure 6: Energy Harvesting System without Energy Storage

Figure 7 shows a multi-source energy harvesting concept. It combines the energy from different environmental sources to guarantee constant or a more reliable power supply for the connected electronic system.

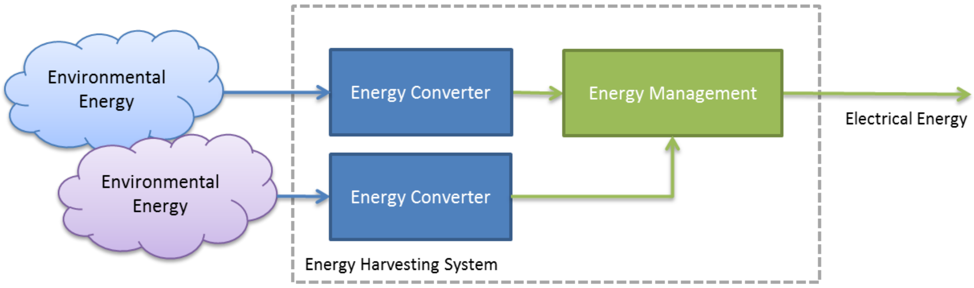


Figure 7: Multi-Source Energy Harvesting System without Energy Storage

Figure 8 shows an energy harvesting system which includes an energy storage device as well as a power/energy management unit. This architecture allows the system to operate even if no environmental energy is available. In this case the system operates from the superfluous energy that was stored before.
The advantage is that the connected electronic system can be supplied continuously. This enables this system to operate for instance a Real Time Clock (RTC), listening remote control commands or monitor environmental variables continuously.

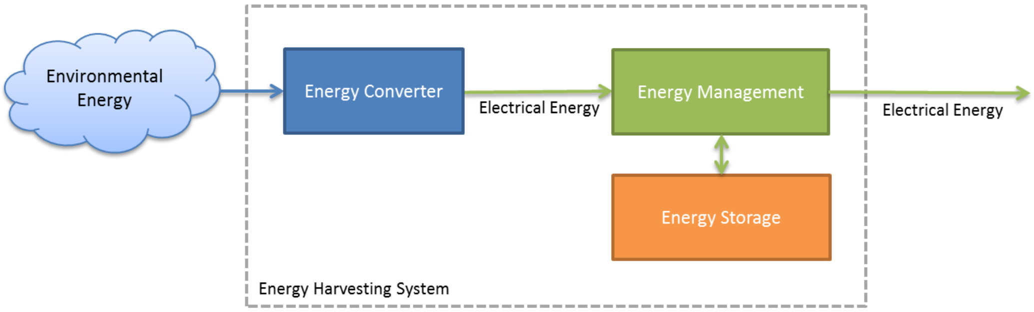


Figure 8: Energy Harvesting System with Energy Storage

Beside the requirement for continuous operation there is another cause for energy storages. If the supplied system requires more power for an action (e.g. RF transition) than the power converter can deliver it is necessary to buffer energy preemptive.

Figure 9 shows how an energy harvesting system is integrated into a self-sufficient sensor or actuator node. The energy required for the operation of the system is obtained from the environment. The system can measure and/or manipulate environmental variables. Communication to other devices is also possible.

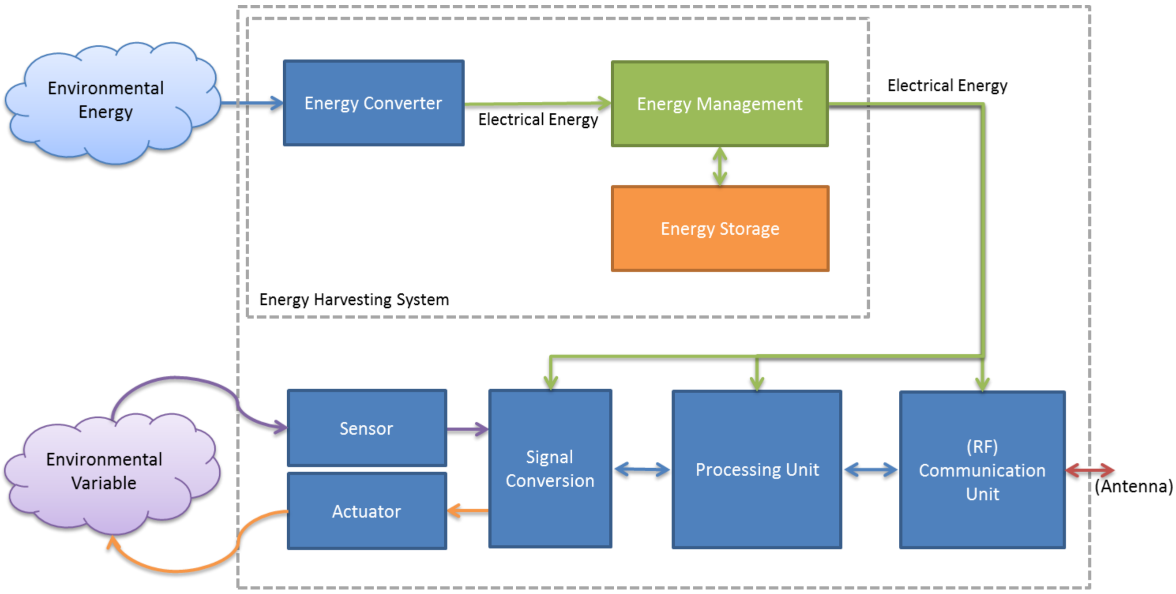


Figure 9: Energy Harvesting System for Sensor/Actuator Nodes

2. RF Energy Harvesting

2.1 UHF RFID Fundamentals

The main fields of applications for UHF RFID technology are supply chain management and logistics. This technology ensures that operating distances of several meters are realizable.

UHF RFID Systems typically operate in the frequency band from 860 MHz to 960 MHz or in the ISM Band at 2.45 GHz. In this work all analysis is done for a frequency of 915 MHz.

For logistic and warehouse applications RFID systems based on the standards ISO18000-6A/B/C and EPC class 0/1 are widely used.

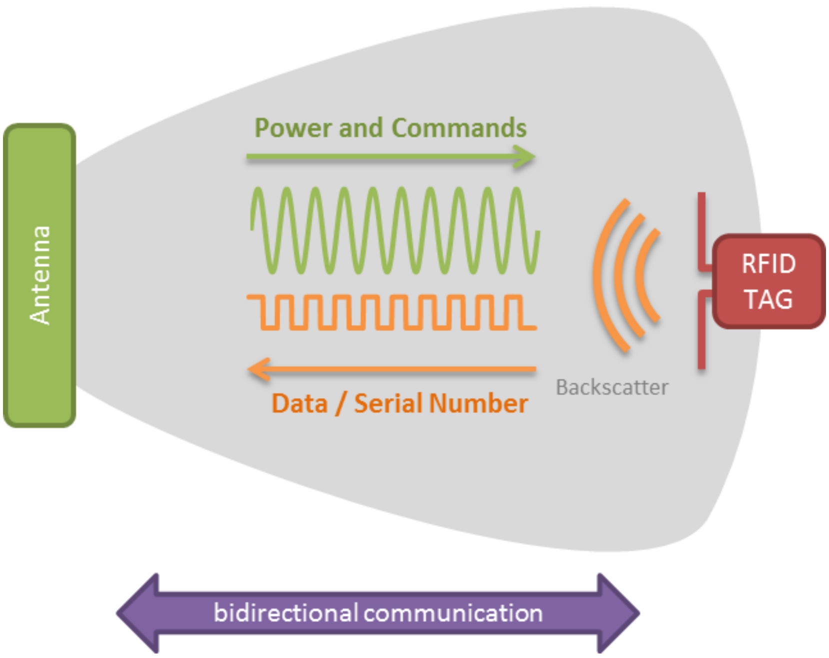


Figure 10: UHF RFID working principle

A UHF RFID tag requires no external power supply for contactless operation. The contactless interface of the RFID tag generates the required power from an antenna circuit. Electromagnetic wave propagation is used for energy transmission between RFID reader (Interrogator) and tag. The required clock signal for the RFID tags operation is generated by an on-chip oscillator. The transmitted data from the interrogator (RFID reader) is demodulated by the tags RF interface. The tags RF-interface also can modulate the electromagnetic field by changing its input impedance. This technique is called backscatter and used for communication from the tag to the interrogator.

Passive UHF RFID tags can operate without a battery. There is also no need for line of sight between interrogator and tag as it is required for bar codes. As long as the tag or label is within the interrogator’s operating range, the tag can communicate using its wireless interface in both directions.

2.1.1 UHF RFID Communication Principle

Forward Link

The forward link describes the communication from a reader device to a tag. In this direction Amplitude Modulation (AM) or Phase Shift Keying (PSK) is used to send digital symbols to the transponder. The data symbols are encoded in a way that ensures that regardless of the data always sufficient power is transmitted in average.

Return Link

One reason why passive RFID transponders can be built very cheap is that they don't have a dedicated radio transmitter. Backscatter radio links are used instead. The return link communication (Tag -> Reader) is done by varying the signal (modulation) that is reflected back to the reader device.

Backscatter

A current flowing in a transmitting antenna induces a voltage on a receiving antenna. If the antenna terminals are left open, then no current flow is possible. This means that no energy is reflected in this case. However if a load is applied to the antenna terminals then the induced voltage causes a current flow. This current has opposite direction by the principle of reciprocity. That means that this current counteracts to its cause and reflects energy which is also known as the backscattered signal.

In hardware this backscatter modulation is done by simply attaching a transistor that acts as the antenna's load. By turning the transistor on and off, the antenna's load impedance changes as well as the amount of reflected power.

The signal used to control the transistor is typically a baseband signal of a few hundred kHz in most cases.

2.1.2 Equivalent Isotropic Radiated Power

The Equivalent Isotropic Radiated Power (EIRP) is the amount of power that a hypothetical antenna with even power distribution in all directions would emit to generate the same peak power density in antennas main beam (direction of antennas maximum gain). [9]

EIRP is often used explicitly as a regulatory limitation on radio operations. A reason for that is that EIRP defines the peak power density of field generated by the transmitter in a particular distance. This is more meaningful than a power output limitation because with the use of different antennas various power density levels could be generated.

2.1.3 Effective Radiated Power

The Effective Radiated Power (ERP) is defined by the United States FCC as follows. Instead of referencing the power to isotropic radiation like EIRP does, ERP is referenced to a half-wave dipole antenna gain. [9], [4]

Because the half-wave dipole antenna has a gain of 2.15 dBi at its peak power point the connection to EIRP can be defined as follows.

$$EIRP = ERP + 2.16dBi = ERP * 1.64$$

2.2 Theoretical Power Limitation for UHF RFID (Link Budget)

2.2.1 Friis Formula

S_T ... *power density*
P_{tx} ... *transmitter power*
A_{rx}^{eff} ... *effective receiving antenna area*
G_{tx} ... *transmitting antenna gain*
R ... *distance to transmitting antenna*

Surface Area of a sphere: $A = 4\,\pi\,R^2$

$$S_T = \frac{P_{tx}}{4\,\pi\,R^2} \cdot G_{tx}$$

S_T Describes the power density (power per area) in a certain distance to the transmitter

$$A_{rx}^{eff} = \frac{G_{rx}\,\lambda^2}{4\,\pi}$$

$$P_{rx} = S_T \cdot A_{rx}^{eff} = \frac{P_{tx} G_{tx} A_{rx}^{eff}}{4\,\pi\,R^2}$$

By transformation of the upper equations the well-known representation of the Friis transmission formula can be reached.

Friis Transmission Formula

P_{tx} ... *input power of the transmittng antenna*
P_{rx} ... *output power of the receiving antenna*
G_{tx} ... *gain of the transmitting antenna*
G_{rx} ... *gain of the receiving antenna*
λ ... *wavelength*
R ... *distance between both antenna*

$$\frac{P_{rx}}{P_{tx}} = G_{tx} G_{rx} \left(\frac{\lambda}{4\,\pi\,R}\right)^2$$

If the gain and power units are in dB then the equation can be modified to the following form.

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} + 20 * \log_{10}\left(\frac{\lambda}{4\,\pi\,R}\right)$$

This simple form is only valid under ideal conditions. These conditions are:

- Free space wave propagation (no multipath and unobstructed)
- R has to be much greater than λ. This means that the field vector of the electric and the magnetic field are perpendicular to each other.
- The antennas are oriented in the right way (alignment and polarization)
- The antennas are perfectly conjugate matched to the system behind
- P_{rx} and P_{tx} is meant as the power directly at the antenna port

- The signals bandwidth is so narrow that it can be assumed as a single frequency for the calculation

Extended version of basic Friis transmission equation considering antenna polarization and alignment, impedance mismatch and non-free space propagation:

$$\begin{aligned}
&\alpha \ldots absorption\ coefficient \\
&\theta \ldots hoizontal\ orientation\ ange \\
&\phi \ldots vertical\ orientation\ angle \\
&\Gamma_{tx} \ldots reflection\ coefficient\ transmitting\ antenna \\
&\Gamma_{rx} \ldots reflection\ coefficient\ receiving\ antenna \\
&\boldsymbol{a}_{tx}, \boldsymbol{a}_{rx} \ldots polarization\ vectors\ the\ antennas
\end{aligned}$$

$$P_{rx} = P_{tx}\, G_{tx}(\theta_{tx}, \phi_{tx})\, G_{rx}(\theta_{rx}, \phi_{rx}) \left(\frac{\lambda}{4\,\pi}\right)^2 e^{-\alpha R}\, (1 - |\Gamma_{tx}|^2)(1 - |\Gamma_{rx}|^2)\, |\boldsymbol{a}_{tx} \cdot \boldsymbol{a}_{rx}^*|^2$$

2.2.2 Listen Before Talk

The requirement Listen before Talk (LBT), describes the requirement for a reader that the channel on which the reader wants to send has to be free. This means in more detail that a specific power limit must not be exceeded otherwise the reader is not allowed to transmit. The LBT feature was introduced to ensure that multiple RF systems can coexist in an environment without interfering each other.

2.2.3 Frequency-Hopping Spread Spectrum

Frequency-hopping spread spectrum (FHSS) is a special data communication technique. This method distributes the average power over frequency spectrum more evenly by hopping to different communication channels. The sequence for the frequency change is determined by an algorithm. Mostly a pseudo random number is used as base for this algorithm.

2.3 UHF RFID Radio Regulations

2.3.1 North America/United States

In the United States the normally used UHF RFID frequencies for unlicensed operation are regulated by the FCC in the Paper FCC Part 15C Low Power Transmitters. In the frequency range from 902 MHz to 928 MHz (26 MHz Bandwidth) a maximum conducted output power of 1 W (30 dBm) is allowed. In an additional requirement the antenna gain is limited to 6 dBi. If the antenna gain exceeds 6dBi then the output power has to be reduced by 1 dB for every dB antenna gain over 6 dBi. [9]
This regulative requirements lead to Effective Isotropic Radiated Power (EIRP) of 4 W or 36 dBm.
It is also required that transmitters have to use frequency-hopping spread spectrum (FHSS) with a minimum number of 50 channels and a random non-sequential hop pattern. The average time a channel is occupied shall not exceed 0.4 seconds in a 10 second period. [9]

Summary:

- Frequency: 902 MHz to 928 MHz
- Power: 4 W (EIRP)
- Requirements: FHSS

2.3.2 Europe

In Europe the standards EN302 208 and EN300 220 are applicable for RFID applications. The limits are stronger than in the United States.

EN302 208

This standard defines a frequency range from 865.6 MHz to 867.6 MHz which is equally spaced in 10 channels with a bandwidth of 200 kHz. The maximal allowed output power is 2 W (ERP) which are 3.28 W (EIRP). The system has also to check if the channel is free (LBT) before transmitting is allowed. [4]

EN300 220

This European standard defines one communication channel with 250 kHz bandwidth at 869.4 MHz – 869.6 MHz. In this frequency range the output power has to be limited to 0.5 W (ERP) or 0.82 W (EIRP). An additional requirement for this standard is that the system is only allowed with a duty cycle of 10 % (transmit time). [4]

Summary:

- Frequency: 865.6 MHz to 867.6 MHz
- Power: 3.28 W (EIRP)
- Requirements: LBT

- Frequency: 869.4 MHz to 869.65 MHz
- Power: 0.82 W (EIRP)
- Requirements: 10 % duty cycle

2.3.3 Japan

In Japan the frequency range from 952 MHz to 954 MHz can be used for RFID applications if a license is available. The maximum allowed output power is 4 W (EIRP) with the listen before talk (LBT) requirement.

2.3.4 Others

Singapore

- Frequency: 866 MHz to 869 MHz
- Power: 0.82 W (EIRP)

- Frequency: 920 MHz to 925 MHz
- Power: 3.28 W (EIRP)

Taiwan

- Frequency: 922 MHz to 928 MHz
- Power indoor: 1.64 W (EIRP)
- Power outdoor: 0.82 W (EIRP)
- Requirements: FHSS

New Zealand

- Frequency: 864 MHz to 868 MHz
- Power: 4 W (EIRP)

Australia

- Frequency: 865.6 MHz - 867.6 MHz
- Power: 3.28 W (EIRP)
- Requirements: LBT

2.4 UHF RFID Link Budget

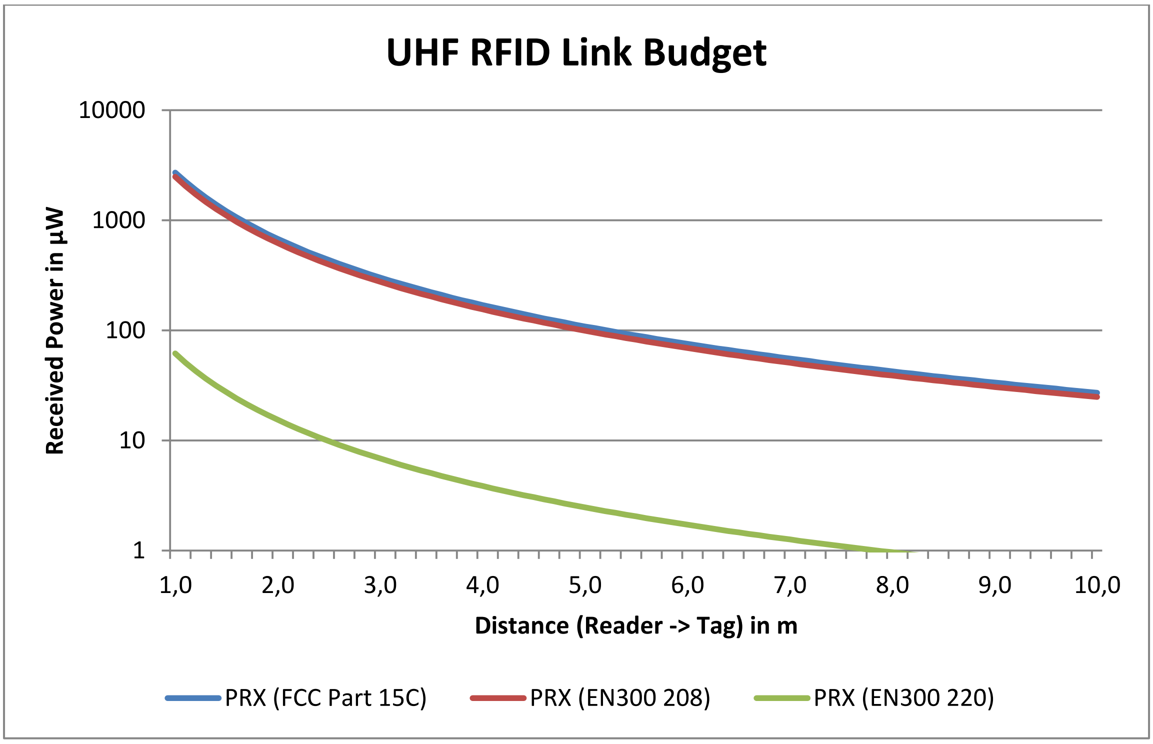


Figure 11: UHF RFID Link Budget

Figure 11 shows the link budget for different RFID reader systems. To fulfill the requirements of radio regulations it is not allowed to transmit with any power. Different regulations lead to different link budgets. For purpose of clarity not all curves are drawn.

It also has to be mentioned that the curves for the link budget are only valid for the following prerequisites.

- RX Antenna Gain: 0 dBi
- Antennas operate in far field
- no obstacles between the antennas
- no reflections (wave superposition)
- ideal antenna orientation

2.4.1 Ambient RF Energy Examples

In today's digital life nearly everybody uses wireless communication devices. Why can that energy of the numerous surrounding transmitters not be used to power self-sufficient electronic systems?

The difficulty when trying to collect the RF power from terrestrial TV transmitter, WLANs, cell phones, mobile phone stations and so on is that the received power level is usually very low. Only for short distances power levels above the µW level can be reached or exceeded.

This fact becomes more clear when thinking about the receive sensitivity of typical wireless communication equipment. The received power is in most cases too low to supply electronic devices. Typical receiver sensitivity of wireless devices is -120 … -60 dBm (fW to nW).

In the following some simple example calculations should clarify that the receive power for typical distances is too low to supply today's electronic devices.

- TV Transmitter (Schöckl):
  Transmitting with ≈100 kW at ≈500 MHz in 15 km distance = ≈1 µW

- Mobile Phone Base Station:
  Transmitting with ≈50 W at ≈900 MHz in 2 km distance = ≈10 nW

- WLAN:
  Transmitting with ≈100 mW at ≈2.4 GHz in 10 m distance -> ≈10 nW

- Mobile Phone:
  Transmitting with ≈2 W maximum at ≈900 MHz in 5 m distance -> ≈50 µW but low duty cycle and transmit power adaption

3. Energy Harvesting RFID IC

NXP Semiconductors, the client of this work, developed an RFID test chip with an Energy Harvesting (EH) output. The major idea of this test chip and this thesis is to find the requirements and improvement opportunities concerning energy harvesting. Additionally the lessons learned during the development process of the prototype are of great value.

Figure 12 shows the basic idea of this test chip on a top level. Power is transmitted from the reader device to the RFID IC. The EH RFID IC transforms the RF energy into DC. From the DC a Microcontroller as well as the connected system is powered. The I²C interface enables the MCU to communicate wirelessly with zero power (backscatter technique).

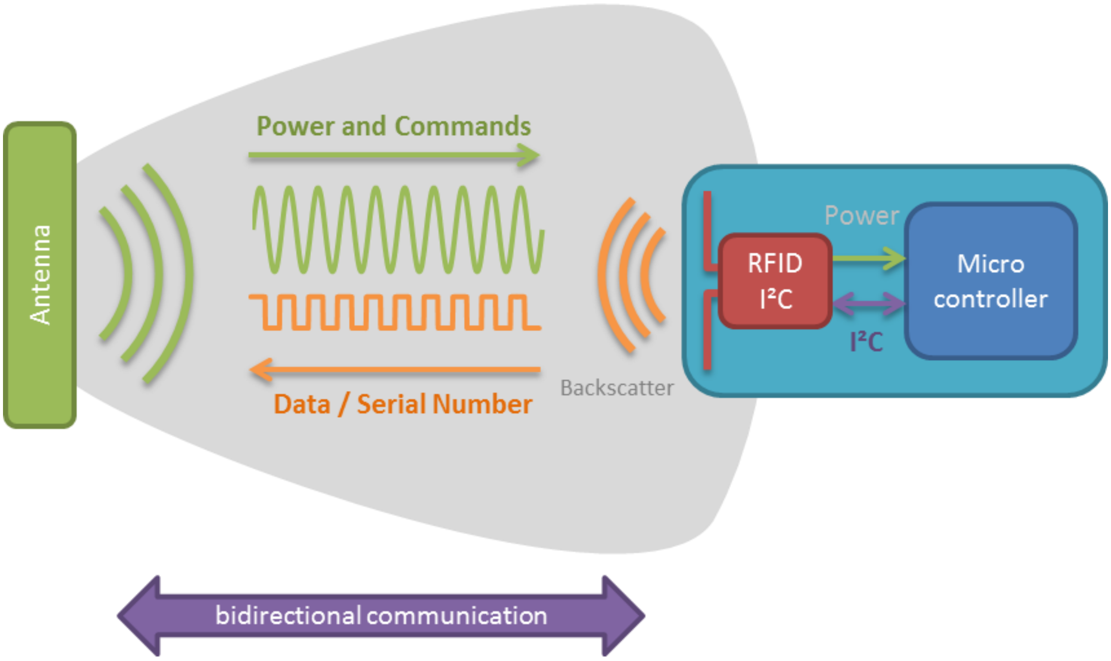


Figure 12: Top Level Working Principle of the EH RFID IC

Functional Description

The introduced EH RFID IC offers the same functionality as usual UHF RFID tags, though it maintains an additional temperature sensor as well as an I²C interface.
There are two possibilities to access the memory. One way is to use the UHF interface and the other is the I²C slave interface.

The EH RFID IC's built in I²C interface needs to be supplied externally because it is not powered from the RF interface. The I²C interface supports standard and fast mode (100 kHz and 400 kHz). It can be used to access the RFID IC memory as well as to take temperature readings.

Additionally a bridge feature is implemented which allows bidirectional data transfer using an SRAM buffer to exchange data between the reader devices and the Micro-Controller Unit (MCU) of the electronic product.

The I²C serial interface enables bidirectional communication between usual UHF RF interface and electronic systems. To access the RFID tag's memory from the RFID reader the MCU not necessarily has to be powered (Figure 13). After power-up of MCU it can read the RFID tag's memory and display the information (Figure 14).

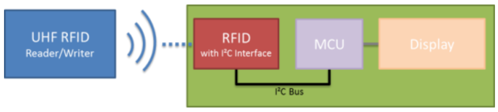


Figure 13: RFID IC supplied from Reader, MCU inactive

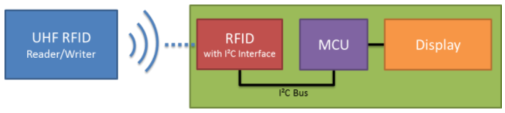


Figure 14: RFID IC supplied from electronic device

The block diagram presented in Figure 15 shows that this IC has two analog frontends. First (upper) frontend is used to power the IC as well as for wireless communication. Second (lower) frontend can be used for energy harvesting applications. Both frontends are constructed equally however the lower frontend has a charge pump connected additionally.

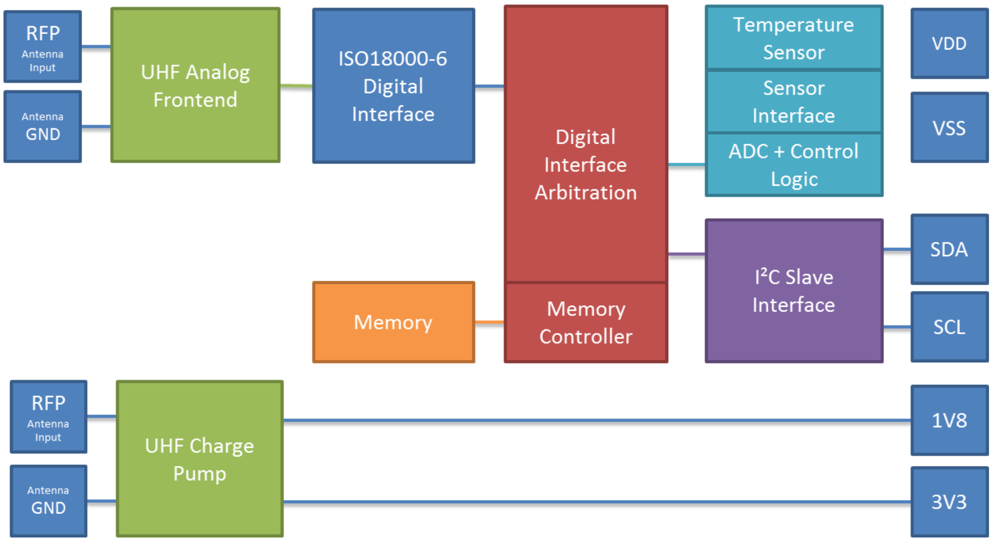


Figure 15: Top Level Block Diagram, Energy Harvesting RFID IC with I²C Interface and Temperature Sensor

4. Energy Harvesting RFID IC Measurements

To measure the available output power, the efficiency as well as the input impedance of the EH RFID IC an automatic measurement setup was developed. The advantage of the setup is to speed up the measurement process which makes it also possible to increase the number of measurement points. The repeatability of an automated setup is also a great benefit.

This setup was developed to determine the available power budget which can be consumed from the prototypes electronic.

With the help of this setup the following dependencies can be analyzed:

- RF input impedance over RF input power level
- DC output power over. RF input power level
- DC output efficiency over RF input power level
- DC output current over RF input power level
- DC output voltage over RF input power level
- RF input impedance over load on DC output
- Dependencies of the RF input frequency

4.1 Wired RF Measurement Setup

4.1.1 Setup Description

The setup shown in Figure 16 consists of a source meter that acts as a programmable load, a Network Analyzer to measure the input impedance (S11 parameters) and a PC to control those instruments. The Control software triggers the instruments in a way that they perform a 2 dimensional sweep. The power sweep is done by the network analyzer and the load sweep is performed with the Source Meter.

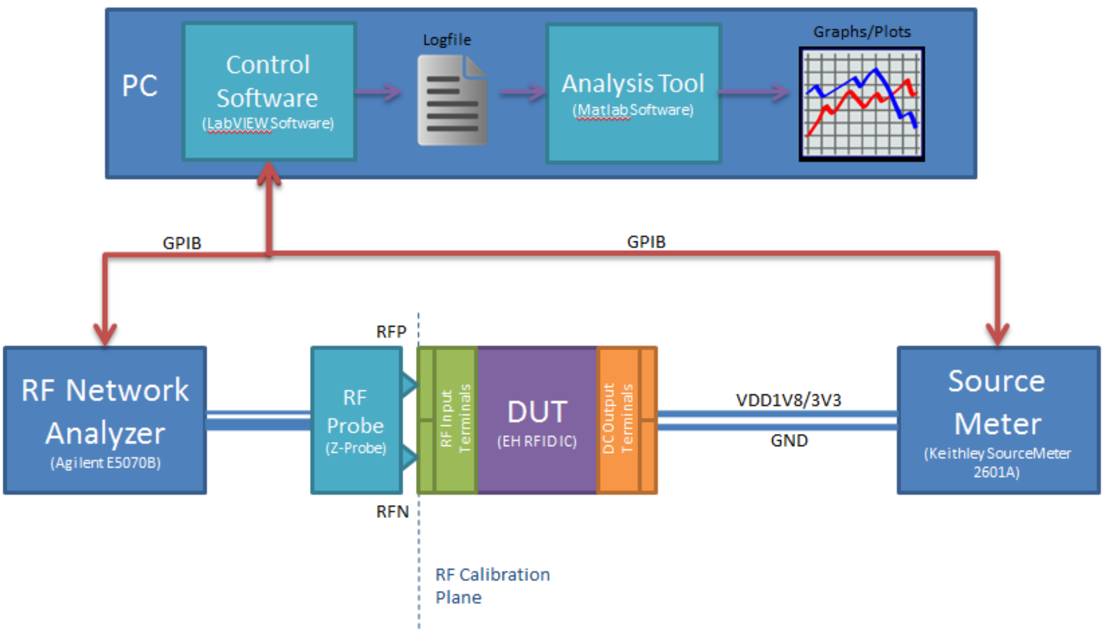


Figure 16: Block Diagram of the Wired RF Measurement Setup

4.1.2 Calibration

The tips of the RF Probe are calibrated using an Impedance Standard Substrate. Doing this has the great advantage that the calibration plane can be set directly to the pins of the package which is very useful for antenna design.

For the calibration process, a 3-Step procedure with open, short and load impedance is used. This calibration process has to be done manually using the built in calibration functions of the network analyzer.

Restriction of the setup:

- Power Levels only up +10 dBm
- No power calibration possible

Figrue 17: RF Probe, Image Source: Cascade Microtech, www.cmicro.com

Figure 18: Impedance Standard Substrate, Image Source: Cascade Microtech, www.cmicro.com

Processing the Measurement Data to Charts:

The log file generated from the control software contains the following data, which consists of two parts, the data from the Source Meter and the data from the Network Analyzer.

Log File Header:

Source Current	Measured Current	Measured Voltage	Power Level	Zin RE	Zin IM
[A]	[A]	[V]	[dBm]	[Ohm]	[Ohm]

Table 2: Data Organization of the Log File

In the first column the set source/sink current values of the Source Meter are listed. In the second and third column the readings for voltage and current from the Source Meter are listed. The other columns are filled with set and measured values from the Network Analyzer.

Each column is separated by a tabulator character. Every row/line represents the data set of a single measurement point.

4.1.3 Virtual Impedance Matching

Because the investigated IC does not have an input impedance of 50 Ohm, like the Network Analyzer has, it is necessary to compensate these deviations virtually in software.

In the first step the reflection coefficient is calculated using the measured impedance and the network analyzer input impedance which is assumed with 50Ω.

$$LF \ldots reflection\ coefficient$$
$$Z_{meas} \ldots measured\ impedance$$
$$Z_{50} \ldots 50\ \Omega\ input\ impedance$$

$$LF = 1 - \left(\left| \frac{Z_{meas} - Z_{50}^*}{Z_{meas} + Z_{50}} \right| \right)^2$$

Because the input power applied to the terminals is known, the power absorbed by the DUT can be calculated using the previously determined reflection coefficient.

$$P_{absorbed} = LF * P_{Input}$$

In the generated plots this technique was used to calculate the real input power for the DUT.

4.1.4 Flowchart of the Measurement Process

Figure 19 shows the measurement process. First a connection to the measurement equipment has to be established. After initialization and configuration the network analyzer starts with performing a power sweep. At each step during the power sweep the source meter measures the voltage and current at the DC output terminals of the DUT. For synchronization between those two instruments a software trigger that is controlled by the measurement program was used. If the analyzer's power sweep is complete, the source meter is reconfigured to simulate another load case. The process of setting the load, performing a power sweep with the network analyzer and measuring the values for each step is done until the system has run through all configured measurement points.

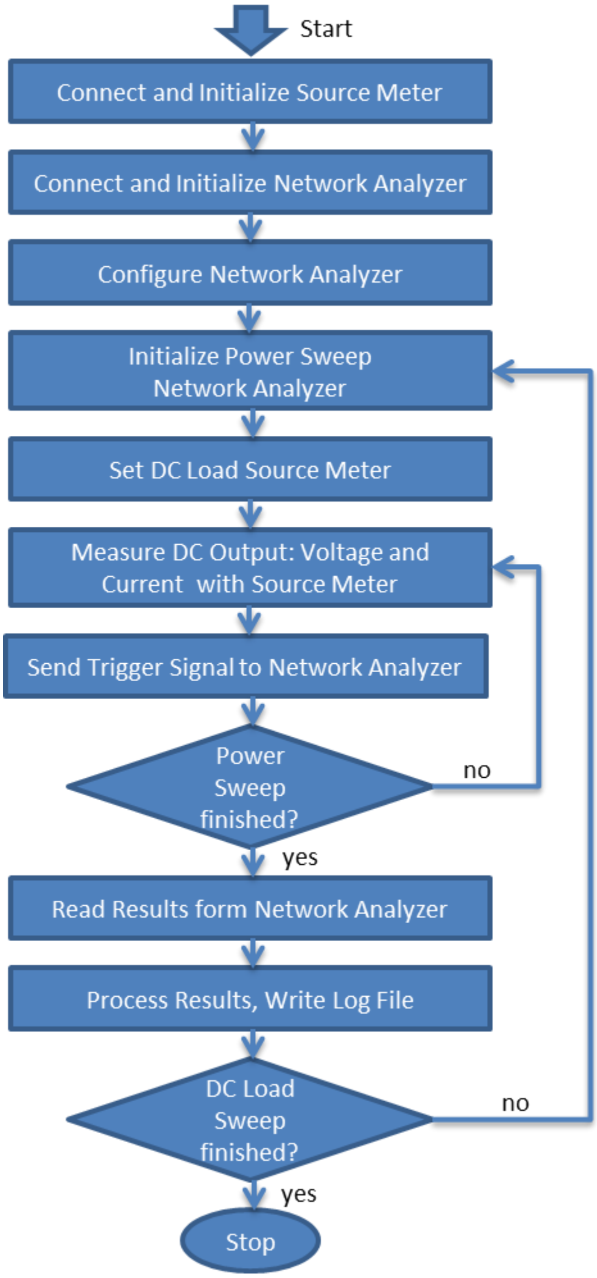


Figure 19: Flowchart of the Measurement Process

4.1.5 Measurement Program

Figure 20 shows the Graphical User Interface (GUI) of the measurement program that controls the instruments and the program flow. Several settings for the Source Meter and the Network Analyzer allow configuring the start and stop points as well as the step size for power and load sweep. There is also an option to disable the Network Analyzer, so that only the load sweep is executed. This is necessary for the wireless measurements when the energy is transmitted over a pair of antennas.

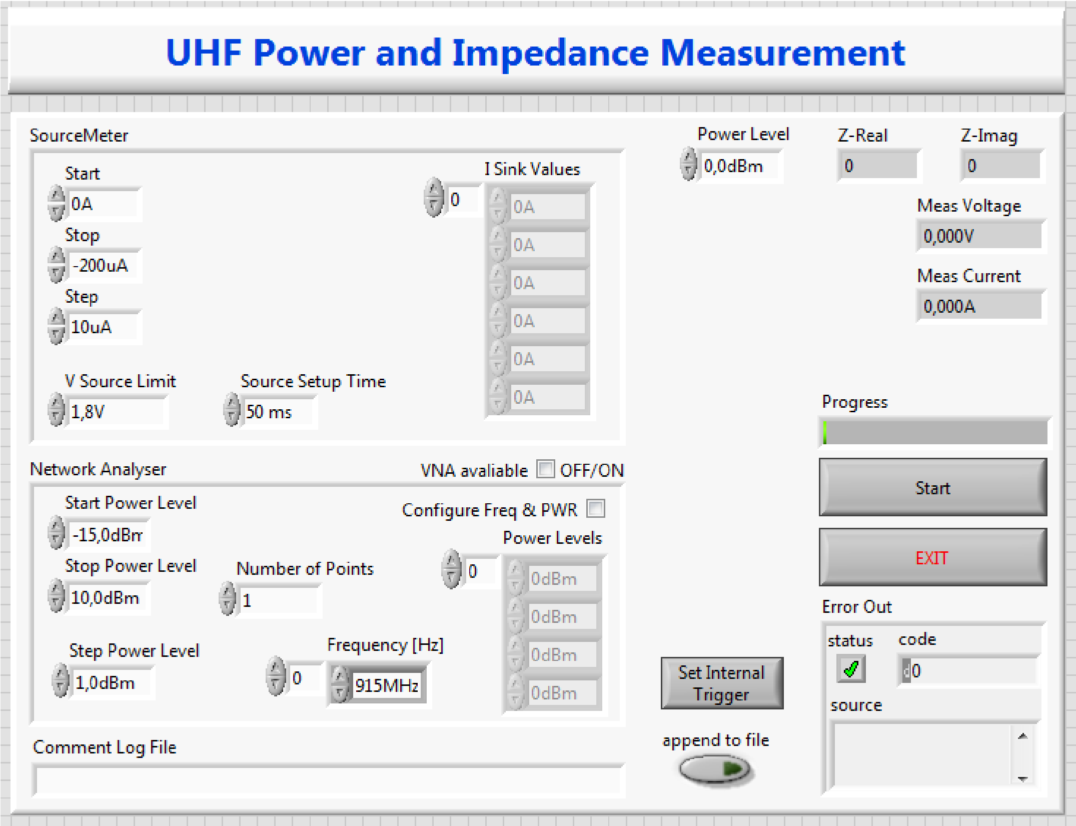


Figure 20: LabVIEW Measurement Program

4.1.6 Micromanipulator Setup

Figure 21 and Figure 22 show the measurement setup. The Micromanipulator is used to exactly connect a pair of UHF probes to the frontend pins of the EH RFID IC's package. The network analyzer is connected to the other end of the probes.
On the DC output of the EH RFID IC wires are directly soldered to the pins. The Source Meter is connected to those pins.

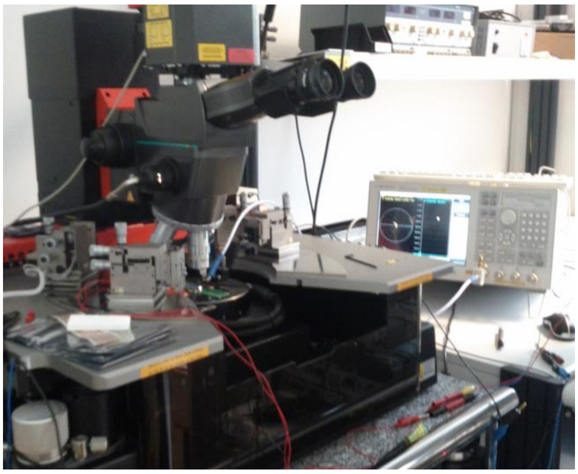


Figure 21: Micromanipulator and Network Analyzer Setup

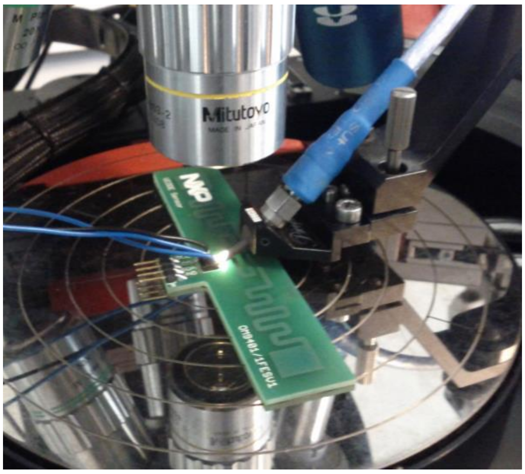


Figure 22: Micromanipulator connecting DC and UHF Probes

4.1.7 Results

In summary for the EH RFID IC the following DC output characteristics are measured:

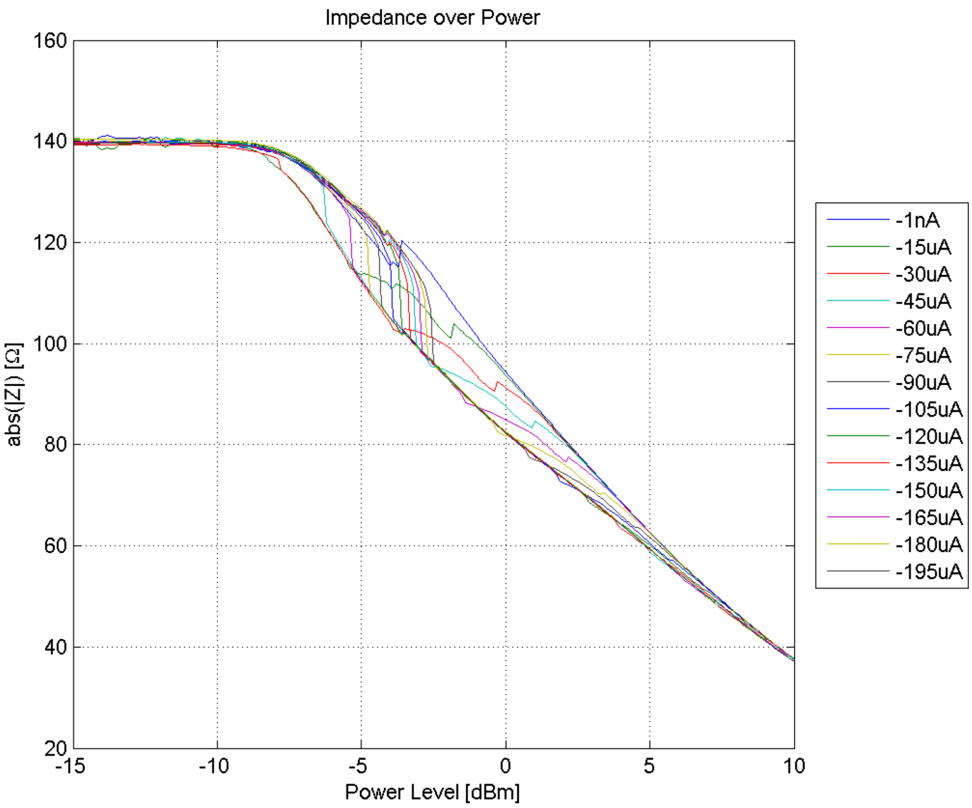


Figure 23: Input Impedance over Power and Load of the EH RFID IC

Figure 23 shows the input impedance of the antenna ports over load and input power level. In can be observed that there is a strong dependency between the frontends input impedance and the applied input power. This behavior is required to ensure that the voltage level at the antenna port does not exceed the limiting voltage of the CMOS process technology. Also it can be seen that there is an influence caused by the load that is connected to the DC output terminals of the IC.

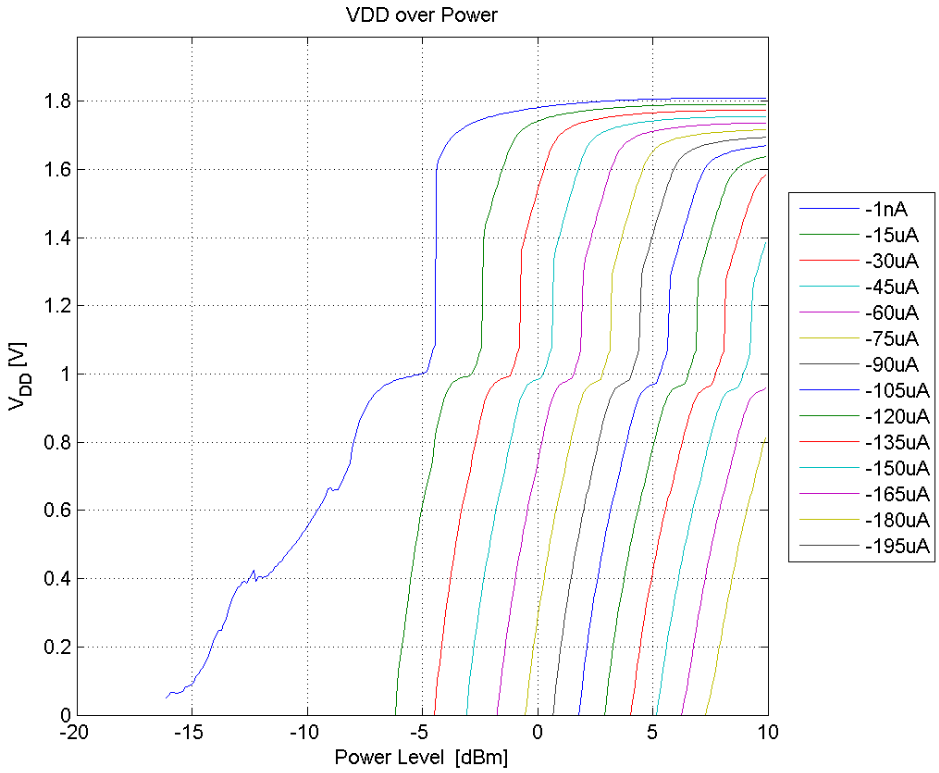


Figure 24: Output voltage for different load cases

Figure 25: Efficiency of the RF to DC conversion

Figure 25 shows the efficiency of the EH RFID IC's RF to DC conversion circuitry. This plot is based on the same measurement data as the plot before. It can be observed that the efficiency of higher input power level decreases. For this behavior the limiting circuitry is responsible for. It sucks up most power to protect the frontend from over voltage. This is done because the RFID frontend is designed and optimized for maximum sensitivity. This means that as soon as the IC has enough power it starts wasting energy. It shows that this frontend architecture is not optimized for energy harvesting applications.

4.2 Wireless RF Measurements

In the previous chapter wired measurements are done to determine input impedance as well as its dependency to the output load. The measurements in this section are done using antennas. That means the power is transmitted over the air, compared to the wired setup these measurements are closer to the application use case.

This setup allows checking and comparing various antenna designs as well as the matching between antenna and the RFID IC's Frontend impedance.

4.2.1 Setup

In Figure 26 the measurement arrangement can be observed. For the signal generation a signal generator and a microwave amplifier were used. To determine the power level which was sent into the transmitting antenna a power meter was connected instead of the antenna to adjust the power level.

On the receiving side the DUT (EH RFID IC) with a special designed antenna was used. On the DC Output terminal of the EH RFID IC a Source Meter was connected that acts as a programmable load. The PC Software that was implemented for 4.1 was used without controlling the network analyzer. Based on this data of the load sweep measured for multiple distances a power over range chart can be generated.

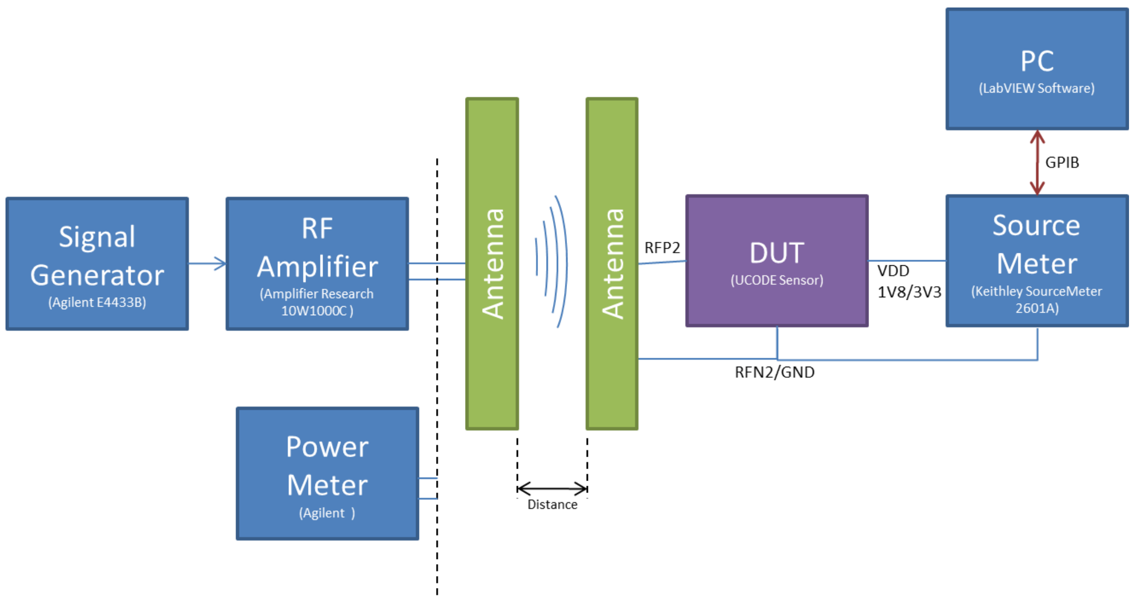


Figure 26: Power Budget Measurement Setup with a pair of Antennas (Wireless)

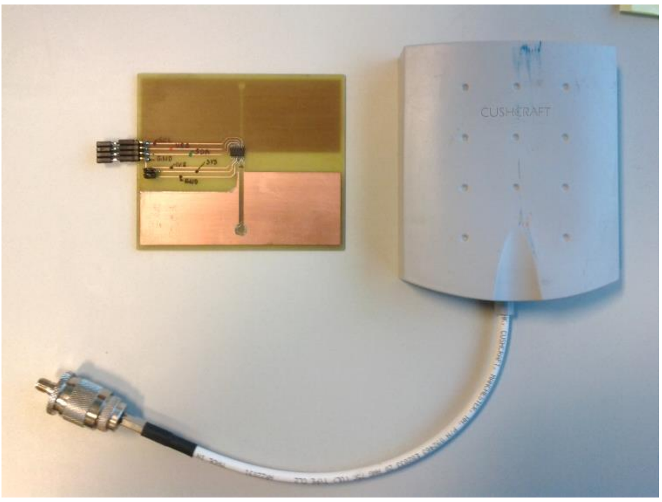


Figure 27: First Antenna Version with EH RFID IC (left), Patch Antenna for Transmitting (right)

Figure 28: High Gain Yagi Antennas for Long Range Measurements

4.2.2 Results

This test is done using +2dBi patch antenna power with +25dBm @ 915MHz. Figure 29 shows the results of the power over range measurement. Figure 30 shows the long range behavior of the antenna.

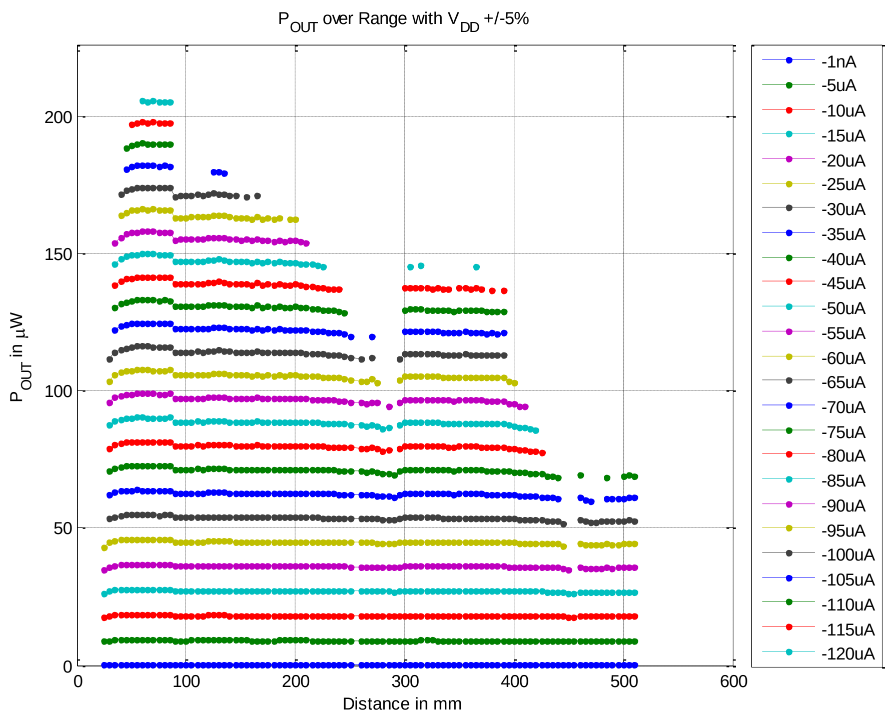


Figure 29: Sensor ANTv2 VDD = 1.8V

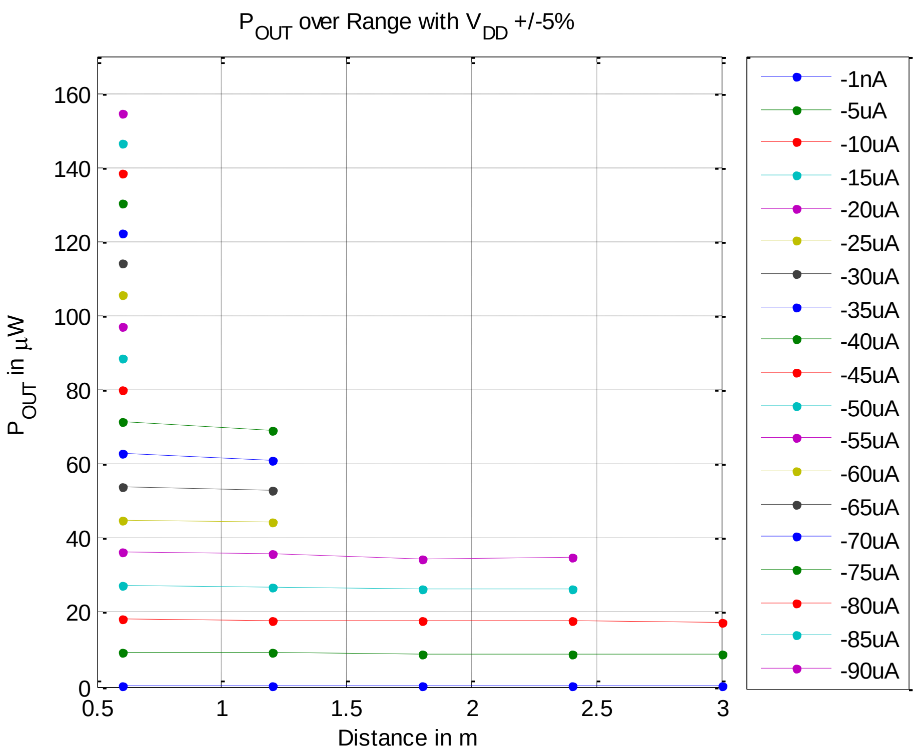


Figure 30: Sensor ANTv2, 27dBm +6dBi 1.8V, Long Range Behavior

DC Power Output Results

VDD 1.8V up to 120µA

VDD 3.3V up to 25µA

4.3 Antenna Comparison

From Figure 15 it can be seen that the EH RFID IC has 2 separated RF frontends. One is for communication and powering the digital logic and the second one does the RF to DC conversion intended for energy harvesting.

The first approach was to design a separated antenna for each of the two RF frontends. The result can be observed from Figure 32. The major disadvantage of this design is its big form factor. Also the performance of the antenna is not the best because it was not optimized to the frontend input impedance in the TSSOP package.

Based on the results from the impedance measurement described in section 4.1 a new antenna was designed from NXP Semiconductors UHF antenna experts. They decided, based on the results, to connect both RF frontends of the EH RFID IC in parallel. This reduces the form factor of the antenna enormously. Connecting the RF frontends in parallel had a second advantage because the imaginary part of the in package impedance was very low which makes it easier to match the antenna. This leads to this simple dipole antenna design.

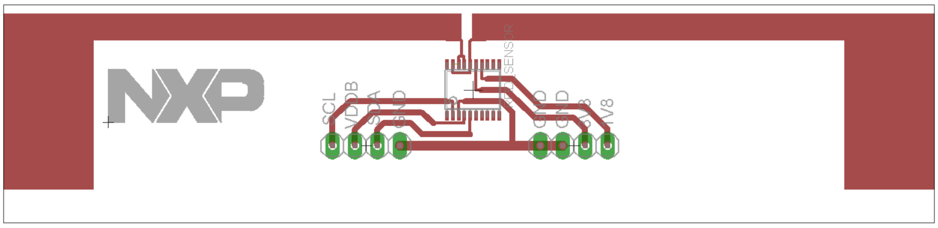


Figure 31: ANTv2

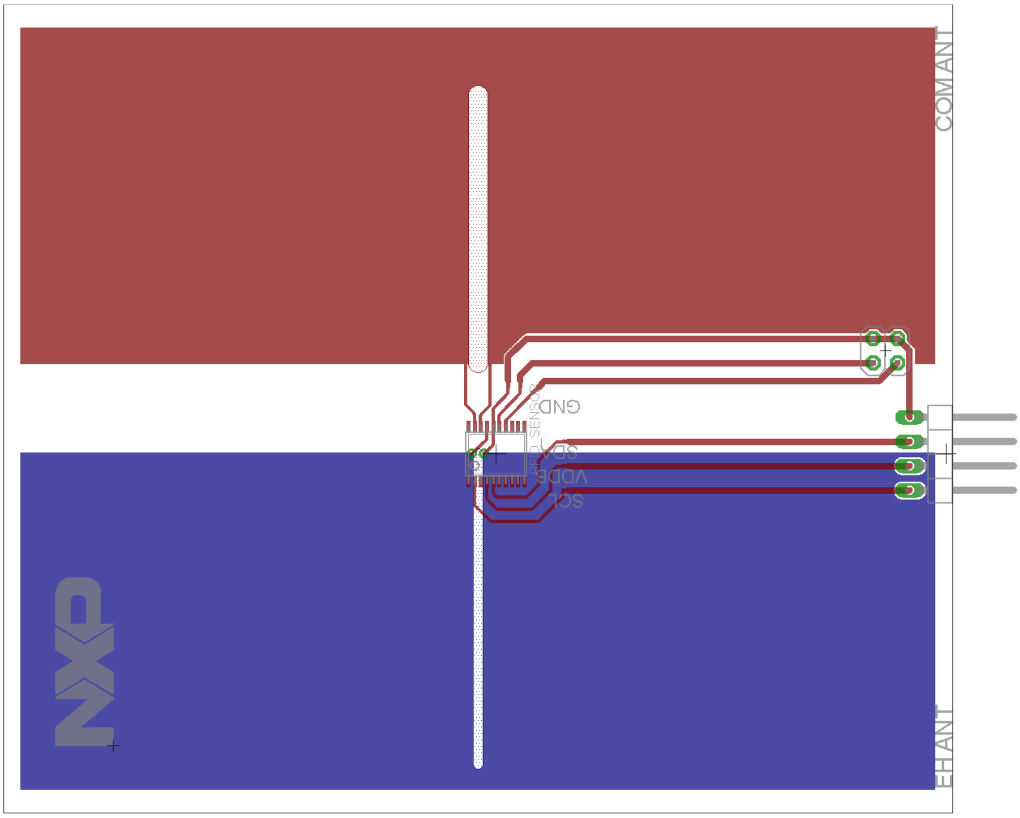


Figure 32: ANTv1.1

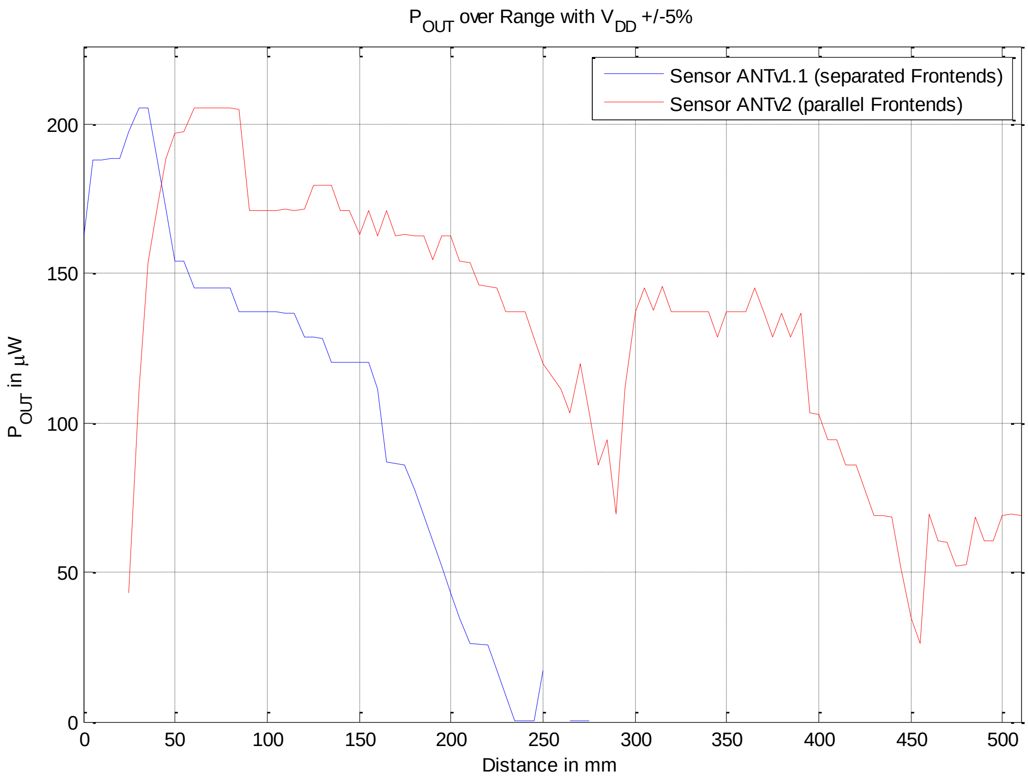


Figure 33: Power over Range, Comparison between ANTv1.1 and ANTv2

In Figure 33 two different antennas are compared for their power ranges. The power output was measured on the 1.8 V pin. Interestingly the ANTv2 with parallel frontends offers a better performance that ANTv1.1 despite is larger sized antenna. Probably this is caused by the poor matching between antenna and frontend.

5. System Components

The figure below shows the general architecture of a semi-active RFID tag with its particular components. In this chapter the requirements for some of the system components are described in more detail.

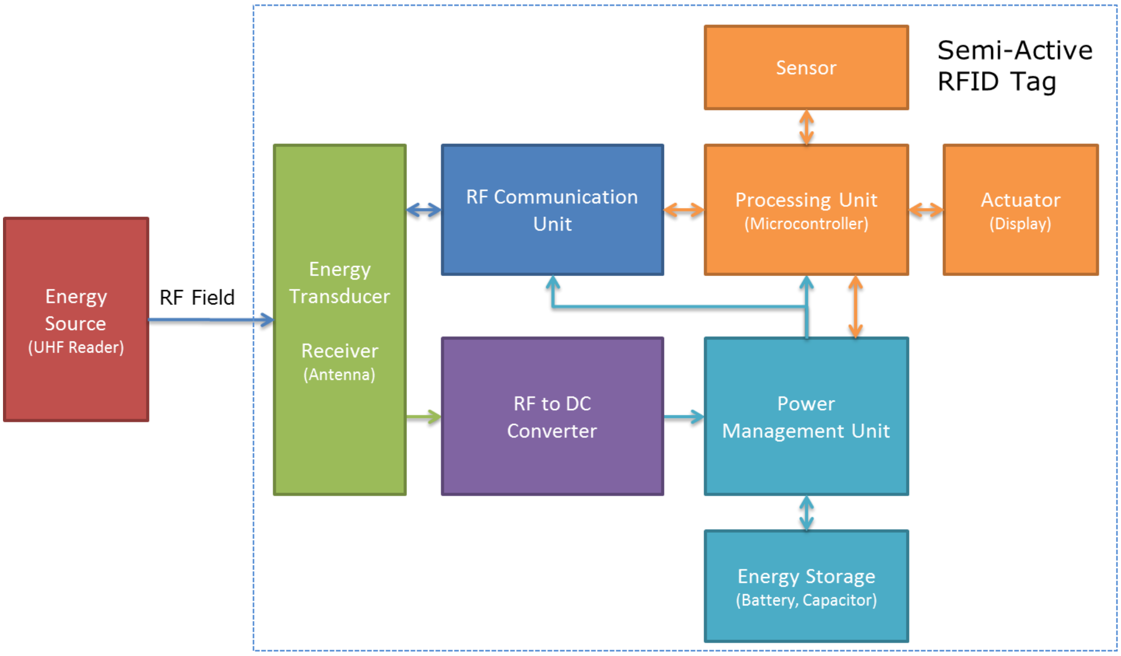


Figure 34: General System Architecture of a Semi-Active RFID Tag

5.1 Electrical Energy Storages Devices

Energy Storage Devices are required to supply, buffer or backup the power rail of electronic circuitry. These storage devices guarantee uninterrupted operation of the electronic system.

Energy storage devices are essential for many applications that use energy harvesting as their primary energy source because:

- Device operating time > time the energy source is available (backup)
- Device’s required power > currently available power from the harvester (buffering)

5.1.1 Rechargeable Battery

Many different types of batteries are available on the market. However not all battery types are suitable to meet the requirement for ultra-low power applications. Choosing the right battery type for a specific application can be very difficult. A lot of properties of the battery type have to be considered. The most important are energy density per weight, energy density per volume, cell voltage, power density (ESR), leakage, charge ability, memory effect, aging, operating temperature range, charge process, under voltage protection, construction shape, hazardous substances or harmful to the environment.

Ni-Cd, Ni-MH battery types are not analyzed in detail because their self-discharge rate is typically high compared to Li-Ion batteries, which makes these battery types unsuitable for this kind of applications.

For the intended purpose in passive smart devices the following two products meet the requirements best.

Cymbet EnerChip™ Solid State Batteries

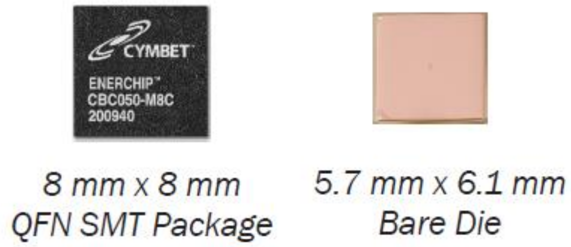


Figure 35: Cymbet Solid State Battery (50µAh, 3.8V), Image Source: [10]

Cymbet offers a Li-Ion type battery that is raised on Silicon Wafer. The die can be packaged to be used in surface-mount technology (SMT). Also the devices are reflow solder-able (tolerant).

Another interesting aspect of this battery type is that it is possible to use die stacking technique to combine battery and IC. For further information it is referred to [11] "A Cubic-Millimeter Energy-Autonomous Wireless Intraocular Pressure Monitor".

Infinite Power Solutions THINERGY Micro-Energy Cells (MEC)

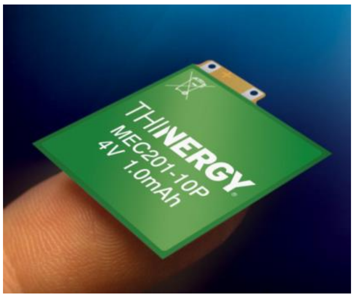


Figure 36: IPS THINERGY Micro-Energy Cell (1mAh, 4V), Image Source: Infinite Power Solutions

The Micro Energy Cells (MEC) from Infinite Power Solutions offer thin film rechargeable batteries based on Li-Ion technology. These batteries have lowest leakage current and comparable good ESR values. Smaller sized cells are also available. The thickness of this battery is only 170µm.

Comparison

Typ	Capacity	Voltage	ESR	Self-discharge Rate (Charge Loss per year)	Calculated Leakage
Cymbet CBC050	50 µAh	3.8 V	0.75 … 4.2 kΩ	1.5%	≈85pA
IPC THINERGY MEC225P	130 µAh	3.9 V	210 Ω	1%	≈150pA
Powerstream PGEB021212	10mAh	3.6 V	-	< 3% per month	<416nA

Table 3: Battery Comparison

Table 3 shows that not every battery is well suited for applications which require low self-discharge rates. Batteries with 5…10% self-discharge rate per month are not uncommon, especially for mobile phone products.

When comparing the properties of these Li-Ion based cells to other battery types the values became even worse. Self-discharge rates of up to 20% for NiCd, 30% for NiMH and Lead Acid 5% per month at room temperature are mentioned in [12].

Only if the battery is optimized for low self-discharge then 2…3% are possible also for NiMH technology.

5.1.2 Capacitor

The usage of a capacitor as main energy storage is very unusual. The prime cause is their poor ratio between size or weight and its capacity. The advantage is that the Equivalent Series Resistance (ESR) is very low which allows fast charge and discharge rates.

The main disadvantage of Electrical Double-Layer Capacitors (EDLC) used as electric energy storage is their high leakage current compared to batteries.

Many EDLC super capacitors are designed for buffering application. Their ESR is then tuned to the mΩ range. Leakage current of hundreds of µA to mA are common. Of course for a sound comparison the leakage currents have to be set in relation to the capacities. However this is mentioned to get an idea.

Typ	Capacity	Voltage	ESR	Leakage
AVX Bestcap BZ113B104Z_B	100 mF	3.6 V	100 mΩ	10 µA
Seiko Instruments Ultracap CPX3225	2.5 mF	2.5 V	25 Ω	10 nA
Panasonic Gold Cap EECEP0E33A	33 mF	2.6 V/3.3 V	350 Ω	5 µA
Panasonic Gold Gap EECER0E153	15 mF	2.6 V	300 Ω	8 µA

Table 4: Ultra Capacitor Comparison

Seiko Instruments CPX3225

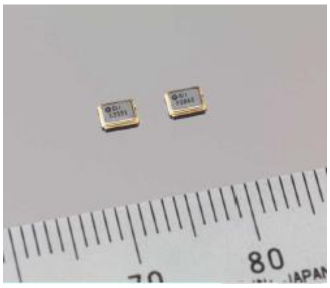


Figure 37: EDLC Chip Capacitor with low leakage, Image Source: Seiko Instruments Inc.

The ultra-capacitor CPX3225 shown in Figure 37 from Seiko Instruments is well-suited for the intended application range. Physical size and leakage current of this capacitor fits perfectly the requirements. However compared to low self-discharge batteries the leakage current is still very high. Also its small capacity can be a limiting factor for some applications.

5.1.3 Primary Coin Cell Battery

Lithium coin cell batteries are often used in electronic devices as power or backup supply. Dependent on their type lithium primary cells have self-discharge rates from 0.5% to 1 % per year. Also special rechargeable (Lithium Manganese) coin cell batteries are available. [13]

This means that this type of battery also can be used. However their charge/discharge cycles are very limited compared to other battery technologies. If done carefully (not exceeding the cut-off voltage) this could be an option to increase the life time (operation time) of a product.

5.2 Power Management System

The power management unit is a very important part for electronic devices which are powered from energy storage devices like batteries. It manages the distribution of the energy and ensures uninterrupted power supply to the connected load.

5.2.1 Battery Management System

"The basic task of Battery Management System (BMS) is to ensure that optimum use is made of the energy inside the battery powering the portable product and that the risk of damage to the battery is prevented. This is achieved by monitoring and controlling the battery's charging and discharging process." [14]

Figure 38 shows the general architecture of a battery management system. The central part is the energy storage itself. A protection circuitry prevents the energy storage from overcharging and deep-discharge. The charger includes a DC/DC or AC/DC converter to charge the storage device with optimal voltage and current level. The DC/DC converter that is connected towards the load should efficiently condition the unregulated voltage of the energy storage to meet the stringent load requirements.

State of Charge represents the amount of charge that is present inside the energy storage device. [14]
The state of charge information is very useful for the connected application to predict its estimated operating time.

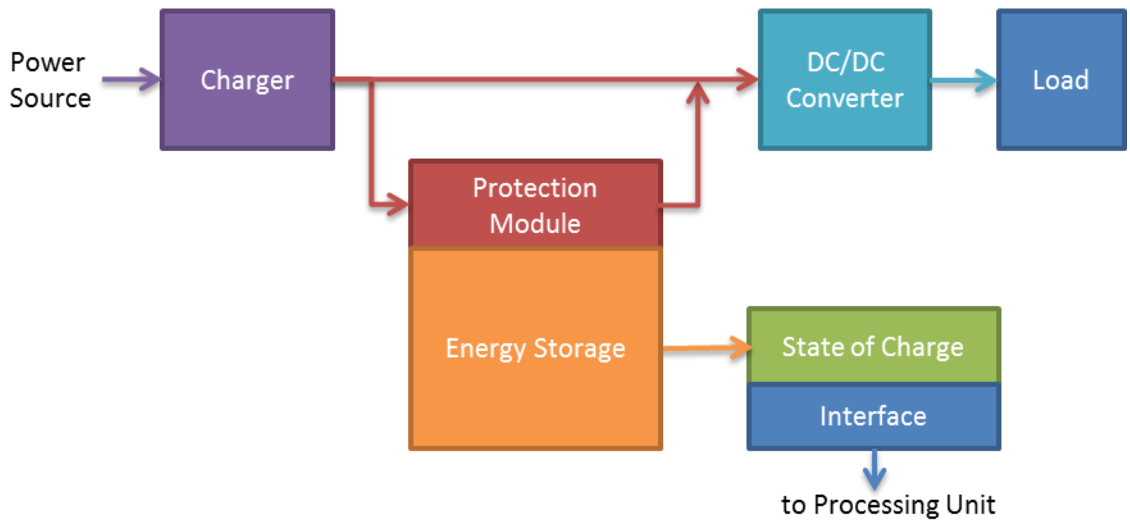


Figure 38: General architecture of a Battery Management Unit [14]

5.2.2 Requirements for Power Management Units used in Energy Harvesting Devices

Features

- Battery charger and protector
  (overcharging protection, battery cell under voltage protection)
- Manage Poor Regulated Power Sources (boost regulator)

Nice to have features

- Regulated Output
- Load Management (high pulse currents)
- Input Power Tracking (maximum peak power point tracking)
- Status and Monitoring of the Energy Storage Device
- Status and Monitoring Input Power Source

Properties

- Low quiescent current
- Deal with low (and high) voltages
- Low Power Boost Charging

5.2.3 Power Management Units for Energy Harvesting

The Electronic Market offers a lot of Power Management Units (PMU) but most of them are not suitable for ultra-low power energy harvesting systems. Typically these PMU's are designed for battery powered handheld devices e.g. mobile phones. Usually the battery capacity is more than 1000 times greater than the battery used for the developed prototype in Section 7.

When dealing with ultra-low power energy harvesting care has to be taken during the selection of components. The quiescence power consumption has to be small compared to the amount of harvested power. Otherwise its use becomes senseless.

Maxim Integrated MAX17710

This Power Management IC is specially designed for energy harvesting applications. It can charge from very low power sources (>1µW) which makes this IC perfectly suited for the intended application. Also a Low Drop Output (LDO) voltage regulator is included.

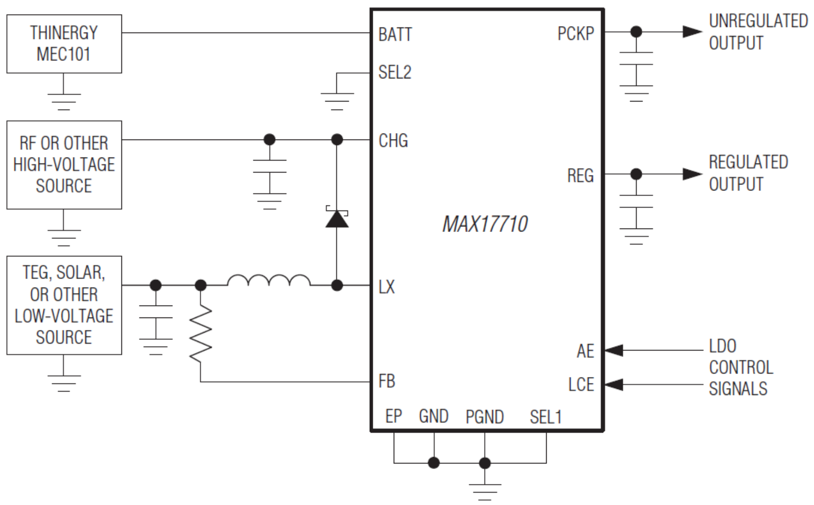


Figure 39: MAX17710 Energy-Harvesting Charger and Protector (Simplified Operating Circuit), Image Source: [15], THINERGY is a registered trademark of Infinite Power Solutions, Inc.

Figure 39 shows a simplified operation circuit of the IC. The boost converter shown on the lower left-hand side can deal with voltage levels below 1V. The LDO voltage regulator offers different operation modes which can be controlled with AE, LCE to ensure low quiescent current consumption.

Cymbet CBC3150

The CBC3150 is a thin film battery with integrated power management. Its main application is backup supply for Real Time Clocks, Micro-controllers, no volatile SRAM or other critical components. However with its integrated charge pump it also can be used for energy harvesting applications.

As displayed in Figure 40 CBC3150's charge pump can be disabled to further decrease its quiescent current when not charging the battery. An indication pin (RESET) that shows if the connected system runs from battery or its primary source is available.

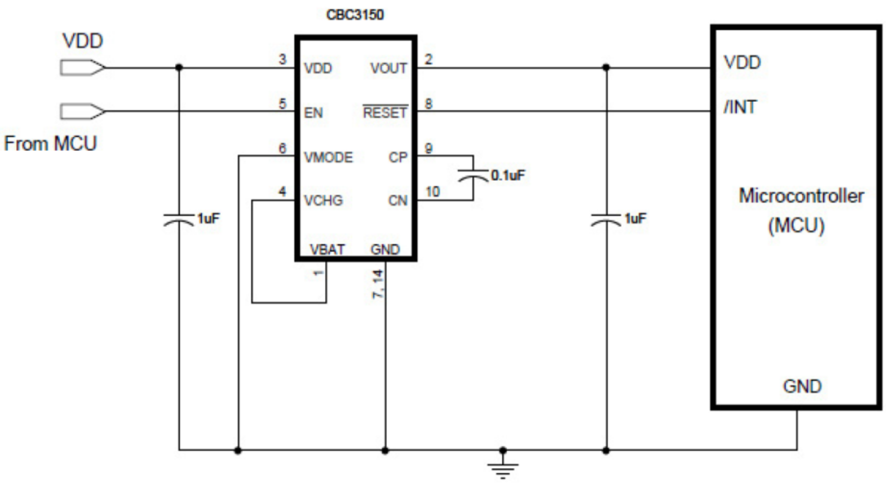


Figure 40: CBC3150 Enerchip CC with Integrated Power Management (Typical Application Circuit), Image Source: [16]

5.3 Display Technologies

One of the most demanded application cases for passive smart devices are remote controllable electronic displays. For instance those displays can appear as an electronic controllable price tag or labels for numerous applications.

5.3.1 LC-Displays

Liquid Crystal Displays (LCD) are low-priced and easily available so they are used commonly in many consumer electronic products. A huge handicap of this display technology is a permanently required power supply for its operation. Most LCD drivers require at least a few µA to keep the content displayed. External graphic LCDs display controllers require typically hundreds of µA which is a handicap for ultra-low power application.

Nevertheless Sharp offers a niche product called "Memory LCD" with very little power consumption. The LS013B4DN04 can hold a static image with typically 6µW. [17]

5.3.2 Electronic Paper

Electronic paper, e-paper or electronic ink is a rising display technology. This display technology offers the appearance of printed paper documents. Electronic paper can hold static text or images indefinitely without using electricity. Electricity is only required during update process. This would be the ideal solution for a wireless self-sufficient system. However the current required updating the display is quite high. This makes the use of e-paper displays for ultra-low power applications challenging.

During the research for this thesis no suitable and available e-paper displays were found. The products obtainable are in most cased not the latest product generation. This leads to the fact that the available RF link budget as well as the energy availability of the energy storage devices doesn't meet the display's power requirements. Additionally charge times of several hours to change the display's content are not accepted.

5.4 Microcontroller

The discussion about the lowest power microcontroller would go too much into implementation details, because most electronic designers have their preferred micro-controller architecture, or other restrictions which inhabit free selection. Additionally selecting the best fitting microcontroller is very time consuming task and very application specific. Most available low power microcontrollers offer similar features. However direct comparison between these features is not possible in most cases.

Therefore only the important features for a low-power micro-controller are mentioned.

Requirements

- Ultra-Low active Power Consumption
- Ultra-Low Standby/Power-Down current
- Fast Wake-up from Power-Down Mode
- Energy Efficient Peripherals
- Low Power (RC) Oscillator

Nice to have features

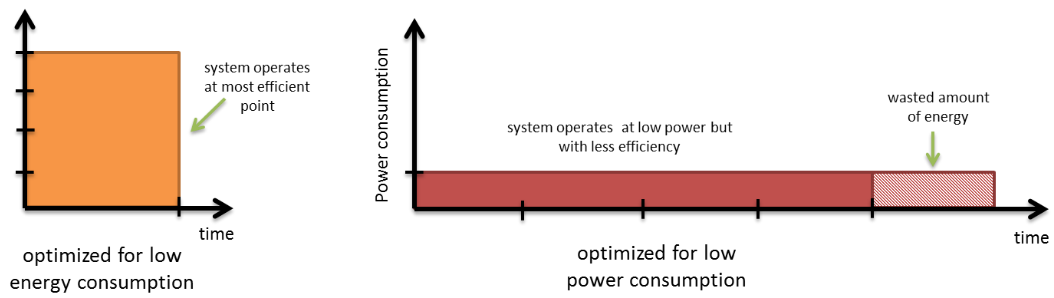
- Autonomous Peripheral Operation
- Direct Memory Access (DMA) for SPI and I²C interfaces
  The main processing unit can go into sleep state while transmitting/receiving
- Perform Tasks without CPU interaction
- Clock Pre-scaling during run time
- Ultra-low Power Low Frequency RC Oscillator
  Very useful if the MCU has to wait until the peripheral hardware has completed its operation. (e.g. often the watch dog timer can be used as a wake up source)

Low-Power Microcontroller product examples: Energy micro EFM32 (ARM Cortex-M0+), Microchip PIC XLP, Texas Instruments MSP430, Atmel AVR picoPower.

6. Design Considerations

6.1 Low Power vs. Low Energy Design

During the design phase it is very important to make a decision, if the system should be optimized towards low power consumption or towards low energy consumption. Often it is thought that these two concepts are the same, but they are not. For low power architectures the efficiency of the part or component is less important because in low power designs it is often easily possible to exchange power consumption with execution time. If it is tried to reduce the energy consumption, the efficiency of the part or component becomes more important. For instance it is possible to select the operation frequency and voltage of the microcontroller to its highest efficient point of computation. It has to be mentioned that systems that are designed with a low energy constraint are typically powered from an energy or charge storage device e.g. battery. A good example for a low power design is a fully passive RFID tag that has only a very little capacitor for buffering. The tag can only survive some micro- to milliseconds from this capacitor. Only the RFID communication protocol limits the maximum execution time for a specific operation. Therefore in the design it is tried to push the power consumption down as far as possible to meet the timing requirements. For the RFID tag this will lead to the maximum operating range. This is one of the reasons why it is so important to clearly know the requirements and limitations of the system that has to be designed.



$$E = P \cdot t$$

Figure 41: Low Power vs. Low Energy, power consumption can often be exchanged with execution time

6.2 Effect of Active and Quiescent Current

Typically a microcontroller and also other system components offer several power-down modes. Dependent on the tasks the system has to perform it spends more or less time in the active or power save mode. The ratio of time between those two modes shows which component has the largest influence to the average power consumption.

If a system spends most time in power save mode then it is a good idea to start optimizing the current that is drawn in power save mode because improvement here has the largest influence to the systems overall power consumption.

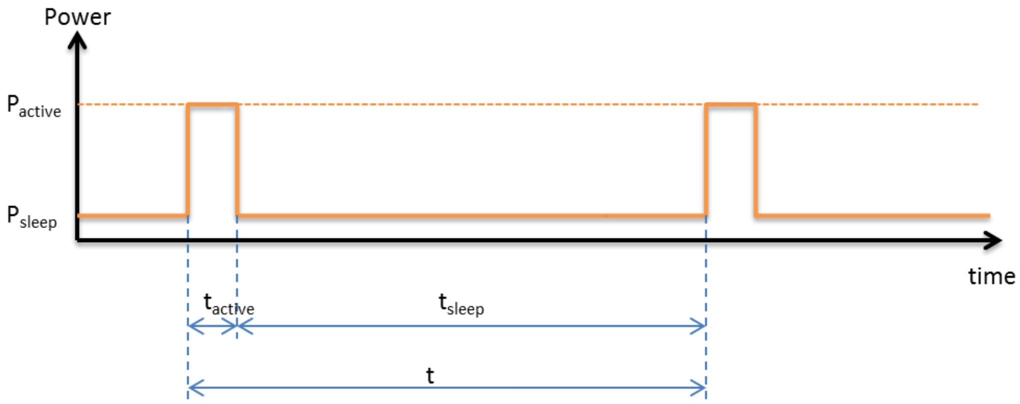


Figure 42: Power Consumption in Active and Sleep Mode

$$P_{avg} = P_{active} \cdot \frac{t_{active}}{t} + P_{sleep} \cdot \frac{t_{sleep}}{t}$$

The following example refers to a temperature logger with different update (measurement) rates. The time required to measure a single temperature sample and save it to memory is equal for every update interval. Only the time between these update steps varies. Meaning that time the electronic system spends in quiescent mode becomes longer.
The result is that for long update intervals the influence of the active current consumption has very little influence to the average. This can be observed in Figure 43 on the right hand side of the chart. The average power consumption is mainly caused by the quiescent current of the system components.

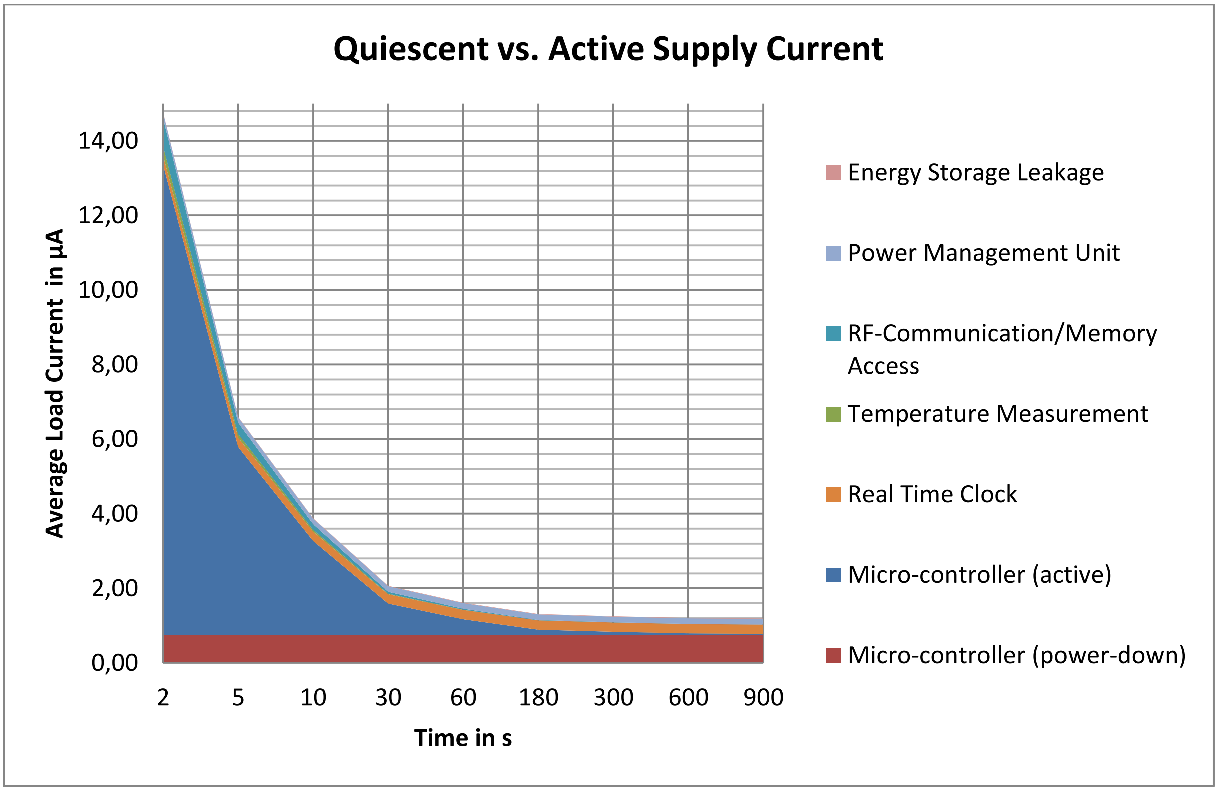


Figure 43: Quiescent vs. Active Supply Current, which influences the system performance most

6.3 Capacitor vs. Battery

Depending on the intended use each storage device has its advantages and disadvantages, these are listed below:

Capacitor

Advantages:

- Low ESR
  (high energy availability)
- Fast Charging Possible
- No cut-off voltage
  (deep-discharge damage)

Disadvantages:

- High Leakage Current
- Difficult to use Entire Energy
- Charging
  (low resistance when empty)

Batteries

Advantages:

- Low Self-Discharge Rate
- Highest Energy Density

Disadvantages:

- Cut-off Voltage (Protection required)
- Charging
  (typically boost converter required)

Figure 44 shows the voltage characteristics in dependency of the stored charge. Rechargeable Batteries have flat discharge curves which is an advantage for the application. The hysteresis of the shown curves is caused due to the ESR of the storage devices.

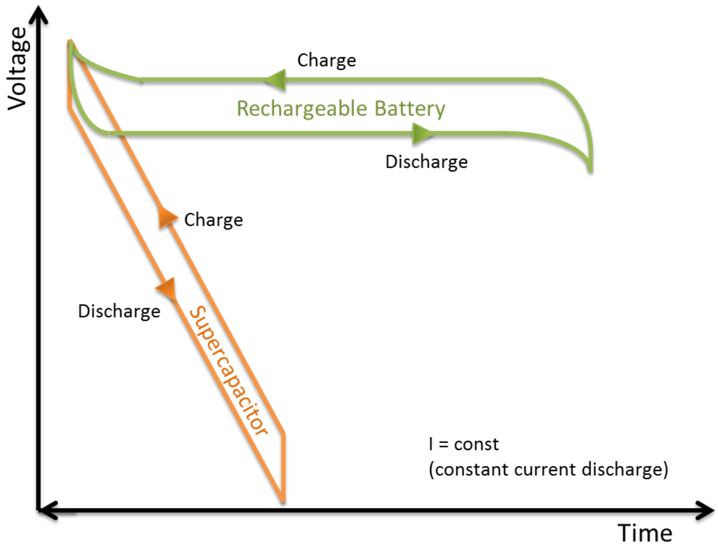


Figure 44: Battery vs. Capacitor, comparison voltage characteristics

Figure 45 shows that capacitors require a pre-charging before the operation voltage range is reached. The initial charge time should be considered in the system design. A huge drawback is that a lot of energy is wasted because only the energy in operating voltage range (ΔU) can be used. To produce relief a boost converter could be used.

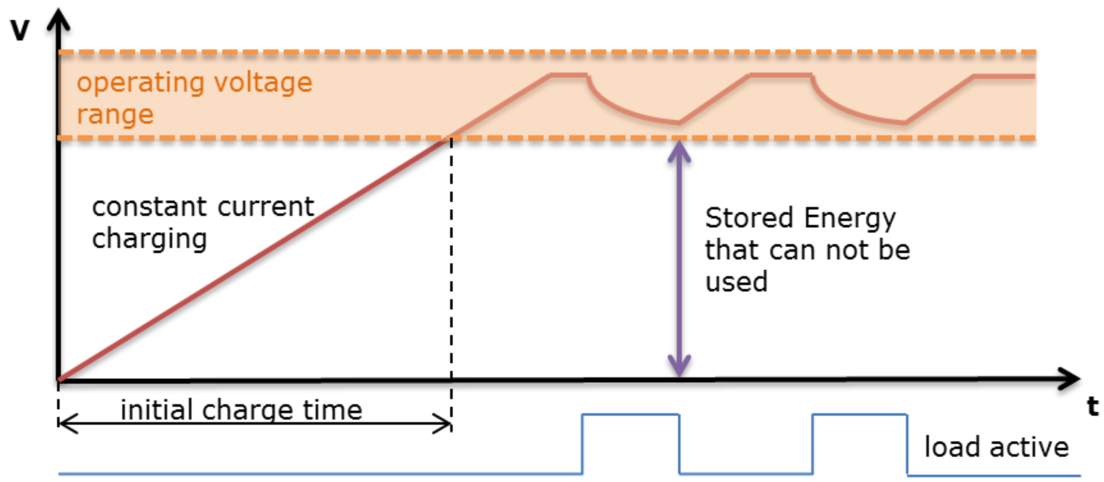


Figure 45: Capacitor voltage behavior

In short summary capacitors are simple to use but their leakage and the large amount of unusable energy are major drawbacks. In contrast rechargeable batteries have very little self-discharge rates, but elaborate circuit design is required (charge controller).

6.4 Energy Storage Charge Time

A big drawback of systems with large energy storages is the charge time. Especially with RF energy harvesting the amount of available power for charging usually is very low. This leads to long charge periods especially if the storage devices capacity is dimensioned to overcome long power outages.

Table 5 shows charge time estimation for different battery capacities and charge currents. The linkage between battery capacities, charge times and charge current is very simple. To get a rough idea if the charge time is acceptable for the intended application it is shown.

		Battery Capacity in µAh				
		10	50	100	500	1000
Charge Current in µA	1	10	50	100	500	1000
	2	5	25	50	250	500
	5	2	10	20	100	200
	10	1	5	10	50	100
	20	0.5	2.5	5	25	50
	50	0.2	1	2	10	20
	100	0.1	0.5	1	5	10

Table 5: Battery Charge Time estimation in hours

Due to the often required voltage boosting a further extension of the charge time has to be considered.

6.5 Selecting the Operating Voltage and Clock Frequency

The systems operating voltage has a big influence on the power consumption as well as on the efficiency of computing. Therefore choosing the right voltage can save power and energy.

In CMOS circuits the power consumption is mainly dependent on the following three factors:

Document [18] describes the composition of power consuming parts in CMOS devices:

$$P_{avg} = P_{switching} + P_{short-circuit} + P_{leakage}$$
$$P_{switching} = \alpha_{0\rightarrow 1} \cdot C_L \cdot V_{DD}^2 \cdot f_{clk}$$
$$P_{short-circuit} = I_{SC} \cdot V_{DD}$$
$$P_{leakage} = I_{leakage} \cdot V_{DD}$$

$$V_{DD} \ldots supply\ voltage$$
$$\alpha_{0\rightarrow 1} \ldots switching\ probability$$
$$C_L \ldots capacitive\ load$$

For digital CMOS circuit e.g. microcontroller typically only the operating voltage and frequency can be selected by the designer on component level. The other factors of these equations are strongly influenced by the parameters of the CMOS process technology. This means that the system designer or user of this CMOS circuits can only select voltage and clock frequency.

It can be observed that the operation voltage of the circuit has influence on all three parts of the equation. Reducing the systems operation voltage will reduce the power consumption as well.

If the energy consumption is considered additionally, the execution time for an operation has also an effect:

$$E = P_{avg} \cdot t$$

The execution time can be influenced by changing the clock frequency f_{clk}. However increasing f_{clk} will also increase $P_{switching}$. To find the most efficient operation point many different factors and constraints have to be considered. For low power designs this is very easy. Just use the lowest operating voltage and clock frequency that is possible to fulfill the requirements.

Note: Often it is even better for low power designs to reduce the operation voltage with a linear voltage regulator that burns the energy than supplying the circuit with the full voltage.

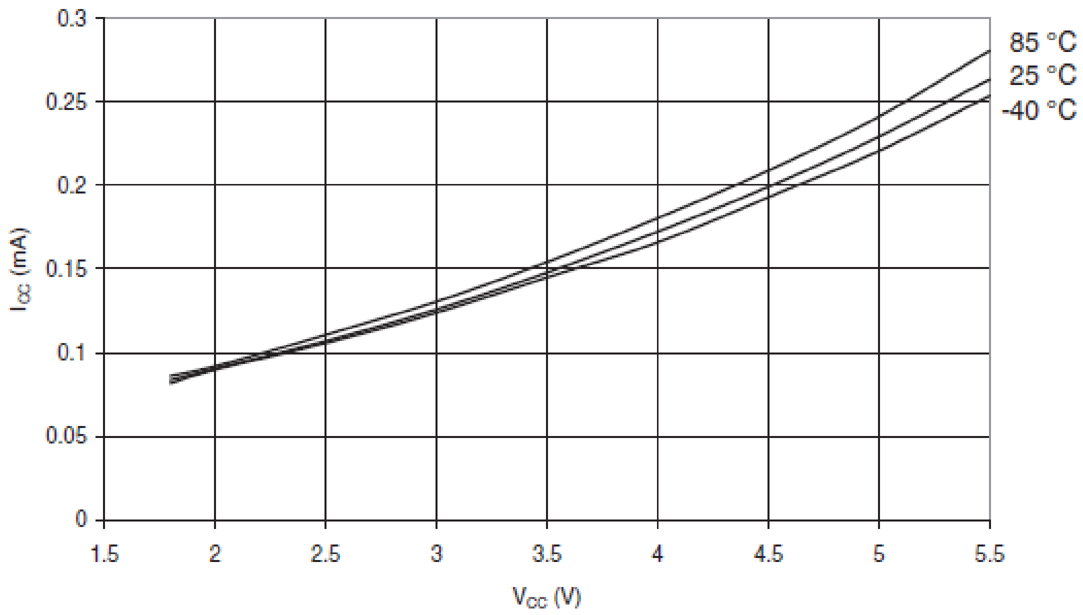


Figure 46: ATmega168PA: Idle Supply Current vs. VCC, Internal RC Oscillator at 1 MHz, Image Source: [19]

If comparing Figure 46 with the equation $P_{switching} = \alpha_{0\to1} \cdot C_L \cdot V_{DD}^2 \cdot f_{clk}$ the quadratic influence of the operating voltage to the devices current consumption can be observed.

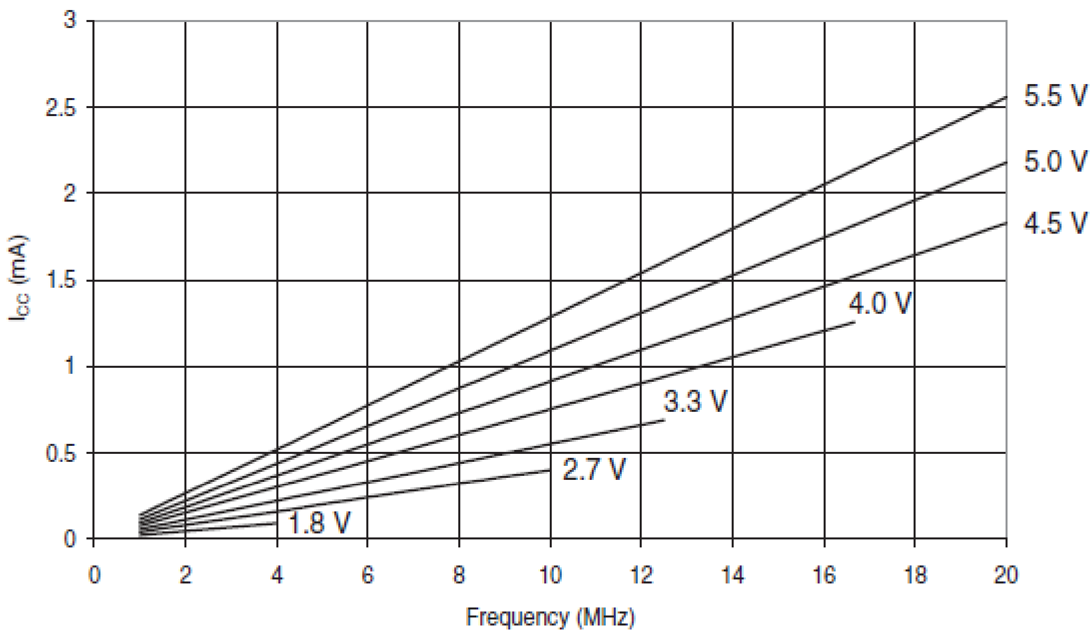


Figure 47: ATmega168PA: Idle Supply Current vs. Frequency from 1 MHz to 20 MHz, Image Source: [19]

Figure 47 shows the linear dependency between clock frequency and current consumption as described in the equation $P_{switching} = \alpha_{0\to1} \cdot C_L \cdot V_{DD}^2 \cdot f_{clk}$
It has to be mentioned that an increase of the frequency can require an increase of the operation voltage too.

6.6 I²C Bus vs. Serial Peripheral Interface (SPI)

In the following the I²C Bus is compared to the SPI. This comparison is focused on power consumption on line level. The comparison does not include the power consumption of the digital logic that is required for handling the communication protocol on the interface. Leakage currents and losses due to switching are also neglected. It is assumed that these factors are very low. The comparison only considers communication time, pull-up resistors and bus capacity. Further it is assumed that on both interfaces equal amounts of data are exchanged.

	I²C Bus	SPI
Clock Frequency	100kHZ, 400kHz, (1MHz) typical	>1MHz typical
Pin count	2 (SDA, SCL)	4 (MOSI, MISO, SCLK, SS)
Device Addressing	Protocol	With Chip Select (Hardware Signal)
Communication Mode	Half-Duplex	Full-Duplex possible
Bus Access	Pull-Up Resistor and Open Collector/Drain (Wired-AND)	Tri-State Outputs (Push/Pull)
Current Consumption	Static current if bus is low	No Static Current Consumption

Table 6: Comparison between I²C Bus and Serial Peripheral Interface (SPI)

6.6.1 Optimize I²C Bus for Low Power/Energy consumption

To use I²C Bus for low power/energy applications the pull-up resistors should be dimensioned to its maximum resistor size. When considering the I²C Bus specification it becomes clear that the maximum pull-up resistor size is only dependent on two factors, bus capacitance and maximum rise time.

The I²C Specification defines the maximum rise time constantly for standard-mode (1µs), fast-mode (0.3µs) and fast-mode plus (0.12µs) I²C-bus devices. [20]

Based on this data a graph can be plotted that shows the maximum possible pull-up resistor size in dependency of the bus capacity and communication speed.

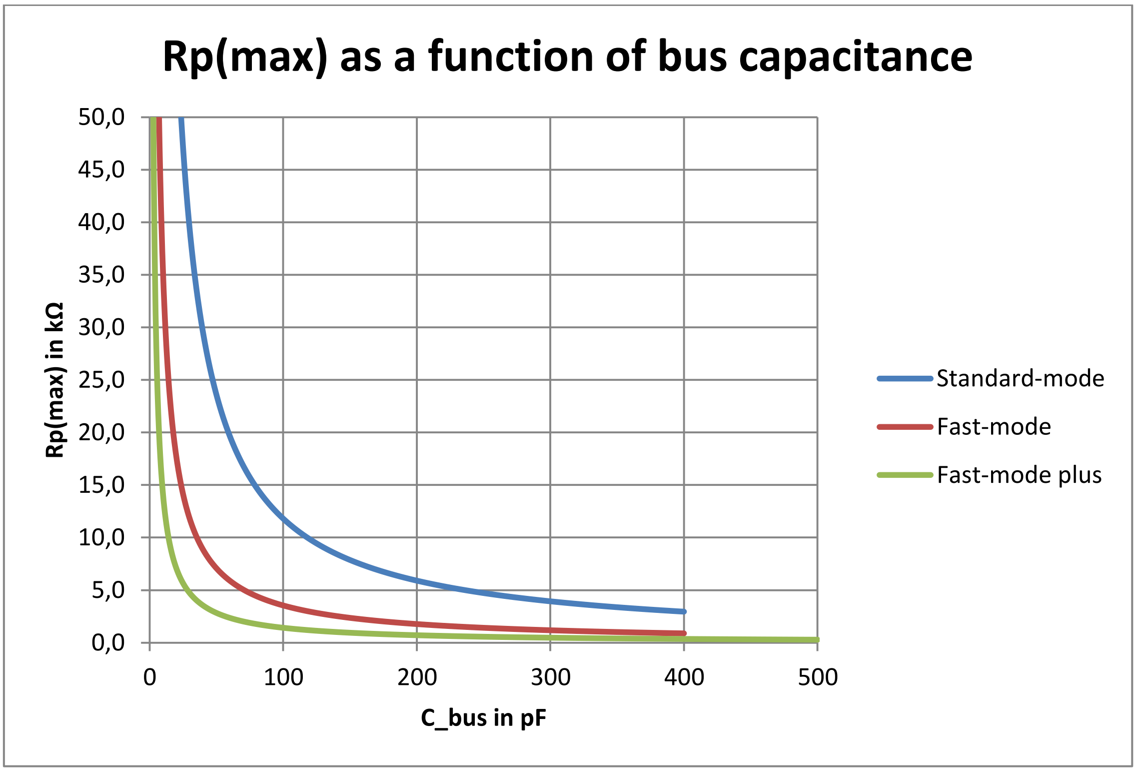


Figure 48: Maximum pull-up resistor size as a function of the bus line capacitance

The rise time t_r is the time required for rising the voltage on the bus line form $V_{IL} = 0.3 \cdot V_{DD}$ (30%) to $V_{IH} = 0.7 \cdot V_{DD}$ (70%).

$$v(t) = V_{DD}\left(1 - e^{-\frac{t}{R \cdot C}}\right)$$

$$V(t_1) = 0.3 \cdot V_{DD} = V_{DD}\left(1 - e^{-\frac{t_1}{R \cdot C}}\right) \rightarrow t_1 = -\ln(0.7) \cdot R \cdot C = 0.35668 \cdot R \cdot C$$

$$V(t_2) = 0.7 \cdot V_{DD} = V_{DD}\left(1 - e^{-\frac{t_2}{R \cdot C}}\right) \rightarrow t_2 = -\ln(0.3) \cdot R \cdot C = 1.20397 \cdot R \cdot C$$

$$t_r = t_2 - t_1 = 0.8473 \cdot R \cdot C$$

$$R_{p_{max}} = \frac{t_r}{0.8473 \cdot C_{bus}}$$

The minimum pull-up resistor size is limited by the supply voltage and the specified/required minimum sink current of an I²C-bus device, but for low power applications it is important to achieve the opposite and keep the pull up resistor sizes as high as possible.
From the perspective of power consumption also the supply voltage should be kept as low as possible because V_{DD}has quadratic influence to the power consumption $P = \frac{V_{DD}^2}{R_p}$ when the bus line is driven low.

I²C, selecting communication speed, clock frequency

Figure 49 shows that running the system at the highest I²C Bus frequency likely offers most energy saving potential. Despite the lower valued pull-up resistors required for operating the bus at higher frequencies.

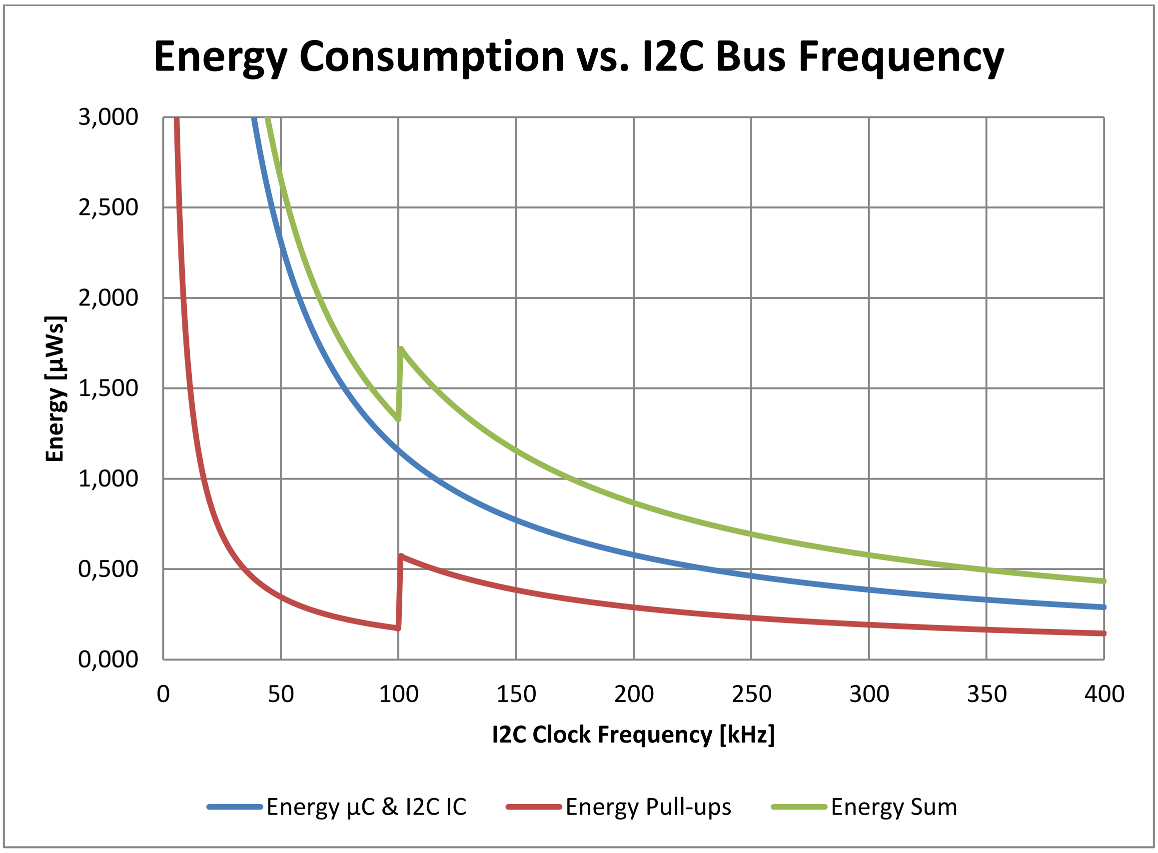


Figure 49: System Energy consumption vs. I²C Bus Frequency

$$V_{DD} = 1.8V, C_{Bus} = 100pF, I_{MCU} = 1.02mA$$

6.6.2 Serial Peripheral Interface Energy Consumption

The Serial Peripheral Interface does not require pull-up resistors. Its main power consumption on line level is caused by the bus capacitance $W = \frac{1}{2} \cdot C_{bus} \cdot V_{DD}^2$. Same as for I²C Bus the operation voltage should be kept as low as possible because V_{DD} has quadratic influence to the energy consumption. SPI has no static power consuming components under ideal conditions. Therefore communication time is less concern for the interfaces energy consumption.

6.6.3 Comparison between I²C and SPI concerning their energy consumption

I²C	SPI
$E = \frac{V_{DD}^2}{R_p} \cdot t_{low} + \frac{1}{2} \cdot C_{bus} \cdot V_{DD}^2$	$E = \frac{1}{2} \cdot C_{bus} \cdot V_{DD}^2$
Example Standard Mode:	
100kHz	1MHz
$\mathrm{C_{bus}} = 2 \cdot \mathrm{C_{Pin}} + \mathrm{C_{Line}} = 2 \cdot 20\mathrm{pF} + 160\mathrm{pF} = 200\mathrm{pF}$	
$R_{p_{max}} = 5900\Omega$	
Example Fast Mode:	
400kHz	4MHz
$\mathrm{C_{bus}} = 2 \cdot \mathrm{C_{Pin}} + \mathrm{C_{Line}} = 2 \cdot 20\mathrm{pF} + 60\mathrm{pF} = 100\mathrm{pF}$	
$\mathrm{R_{p_{max}}} = 3540\Omega$	

Table 7: Comparison between I²C and SPI concerning their energy consumption on two examples

Estimation Energy Consumption I²C Write Data

Energy Consumption of the SPI interface lines is mainly dependent on the capacity of the bus lines. All other factors that influence the energy consumption (leakage, switching …) are neglected for this estimation.

SDA	Start	Dev Addr	W	ACK	Mem Addr	ACK	Mem Addr	ACK	Data	ACK	Data	ACK	Data	ACK	Data	ACK	Stop
SCL		Clock															

Table 8: Example Protocol for I²C Write Data

Rough estimation of I²C bus power consumption ($f_{clk} = 100kHz, C_{bus} = 200pF$):

$$Bus_{low_{bits}} = \#frames \cdot \#Bits_{per\ frame} \cdot Likelihood_{DATA_0} = 7 \cdot 9bit \cdot 0.5 = 31.5\ bits$$

$$\#Clock_{cycles} = \#frames \cdot \#Bits_{per\ frame} + Stop_{condition} = 7 \cdot 9bit + 1 = 64\ Clock_{cycles}$$

$$Communication\ time: t_{com} \approx \#Clock_{Cycles} \cdot \frac{1}{f_{clk}} \approx 64 \cdot \frac{1}{100kHz} \approx 640\mu s$$

$$t_{SCL_{low}} \approx t_{com} \cdot duty_{cycle} \approx 640\mu s \cdot 0.5 \approx 320\mu s$$

$$t_{SDA_{low}} \approx t_{com} \cdot Likelihood_{DATA_0} \approx 640\mu s \cdot 0.5 \approx 320\mu s$$

$$t_{Bus_{low}} = t_{SCL_{low}} + t_{SDA_{low}} = 640\mu s$$

$$\#edges_{riseing} = \#Clock_{cycles} + \#SDA_{low_{bits}} = 64 + 31.5 = 95.5$$

$$E_{I2C} = \frac{V^2}{R_p} \cdot t_{Bus_{low}} + \frac{1}{2} \cdot C_{bus} \cdot V^2 \cdot \#edges_{riseing}$$
$$= \frac{1.8V^2}{5900\Omega} \cdot 640\mu s + \frac{1}{2} \cdot 200pF \cdot 1.8V^2 \cdot 95.5 = 382.4nJ$$

Estimation Energy Consumption SPI Write Data

MOSI	CMD Code	Mem Addr	Mem Addr	Data	Data	Data	Data	
MISO								ACK
SCLK	Clock							
SS	High							

Table 9: Example Protocol for SPI Write Data

$$\#edges_{MOSI,MISO} = \left(\#Bytes_{MOSI} \cdot \#Bits_{byte} + \#Bytes_{MOSI} \cdot \#Bits_{byte}\right) \cdot Likelihood_{DATA}$$
$$= (7 \cdot 8 + 1 \cdot 8) \cdot \frac{1}{2} = 32\ rising\ edges$$

$$\#edges_{clock} = \#Bytes \cdot \#Bits_{byte} = 64\ rising\ edges$$

$$Communication\ time: t_{com} \approx \#Clock_{Cycles} \cdot \frac{1}{f_{clk}} \approx 64 \cdot \frac{1}{1MHz} \approx 64\mu s$$

$$E_{SPI} = \frac{1}{2} \cdot C_{bus} \cdot V^2 \cdot \#edges_{clock+MOSI+MISO} = \frac{1}{2} \cdot 200pF \cdot 1.8V^2 \cdot 97 = 31.4nJ$$

								compared to SPI	
Typ	**CBus**	**V**	**Rp**	**fclk**	**tcom**	**#edges**	**E**	**Energy Consumption**	**Communication Time**
	pF	*V*	*Ω*	*kHz*	*µs*	*1*	*nJ*	*%*	*%*
I²C	200	1,8	5900	100	640	95,5	382	1217%	1000%
I²C	200	3,3	5900	100	640	95,5	1285	1217%	1000%
I²C	100	1,8	3450	400	160	95,5	166	1055%	1000%
I²C	100	3,3	3450	400	160	95,5	557	1055%	1000%
								compared to I²C	
SPI	200	1,8	-	1000	64	97	31	8%	10%
SPI	200	3,3	-	1000	64	97	106	8%	10%
SPI	100	1,8	-	4000	16	97	16	9%	10%
SPI	100	3,3	-	4000	16	97	53	9%	10%

Table 10: Estimated Energy Consumption Comparison between I²C and SPI

Consumed Energy for charging the bus capacity is almost at level for I²C and SPI. But I²C requires the pull-up resistors which consume the most of the energy in this comparison.

Also the communication time is on the SPI Interface typically about 10 times faster than on I²C Busses.

For the given example the estimated energy consumption of SPI is roughly 15 times lower than on the I2C Bus. If the power consumption of the microcontroller is also taken into account, the amount of saved energy is even higher because the communication time on SPI is lower. This makes the energy saving potential for the SPI Interface even higher.

For many use cases in smart passive devices the microcontroller will spend the most of its most active time for communication with the EH RFID IC. A fraction of this time is required for data handling and calculations. With these assumptions the system with an SPI interface requires about 10 times less energy than the system with I²C bus.

Example, Estimated Energy Consumption Including a Microcontroller:

Microcontroller Unit Power Consumption: ≈1mA at $V_{DD} = 1.8V$and $f_{clk} = 4MHz$ leads to a power consumption of $1800\mu W$

$$E_{SPI} = E_{Bus} + P_{MCU} \cdot t_{com} = 16nJ + 1.8mW \cdot 16\mu s = 45nJ$$

$$E_{I2C} = E_{Bus} + P_{MCU} \cdot t_{com} = 166nJ + 1.8mW \cdot 160\mu s = 454nJ$$

This computational example shows that reducing the communication (active) time of the system can save power.

If choosing the SPI for communication is not an option because of the design requirements, it is proposed to operate the I²C Bus in the following manner. The I²C clock line (SCL) is driven active high and low using a push/pull output driver. Thereby the pull-up resistor for the SCL line becomes obsolete and most of the energy wasted by this part can be saved. However this requires that the I²C Bus is setup in a single master configuration.

Another proposal to reduce the I2C static power consumption during the bus low phase is to replace the pull-up resistors with a voltage controlled current source. The current source is configured in a manner that low current is forced during hard low (e.g. 0% … 5% of V_{DD}) and high current for voltage levels above e.g. 5%.

It has to be mentioned that the shown energy and power estimations are based on many simplifications. Therefore it is recommended to verify costs and benefits on a more detailed basis in simulation of the whole system or on a prototype, to ensure that a sound design decision is taken.

6.7 Architecture Proposals for Self-Sufficient Temperature Logger

In this section, 3 architecture variants are analyzed. All variants use different energy storage devices and power management units.

6.7.1 Variant 1 – Energy Storage Device: Infinite Power Solutions, Thin Film Battery

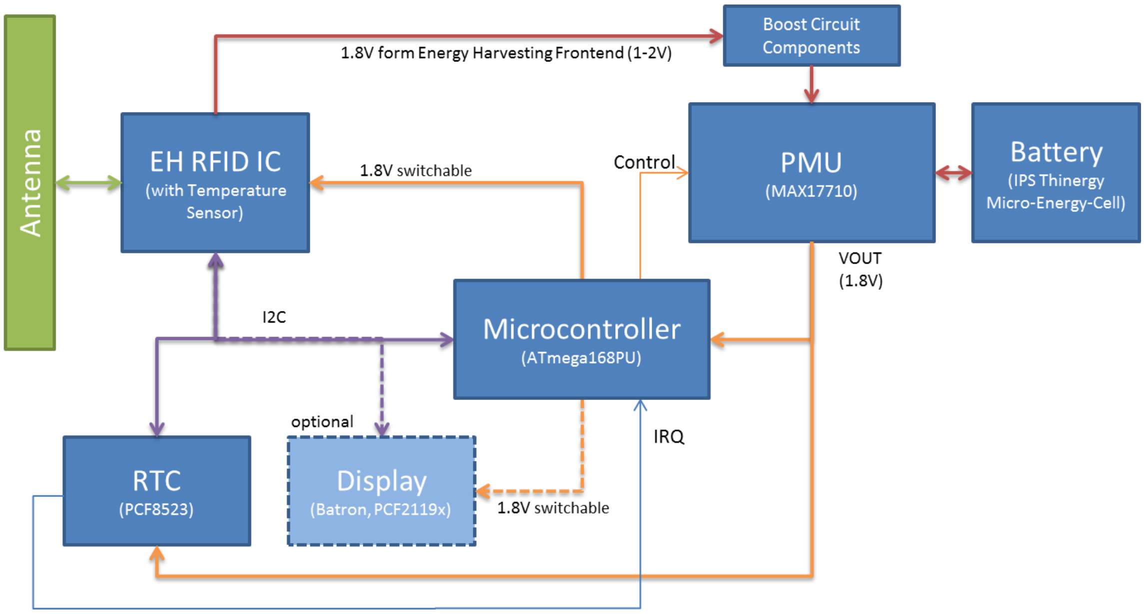


Figure 50: Block Diagram, PMU=MAX17710, Battery=IPS Thinergy MEC

In this System Architecture a Power Management Unit (PMU) which is specially designed for energy harvesting applications is used. The PMU has a built in boost converter to be able to charge the Li-Ion battery cell. Also an ultra-low power voltage regulator is already included in this PMU. This makes this solution very simple and highly effective.

6.7.2 Variant 2 – Energy Storage Device: Cymbet, Solid State Battery

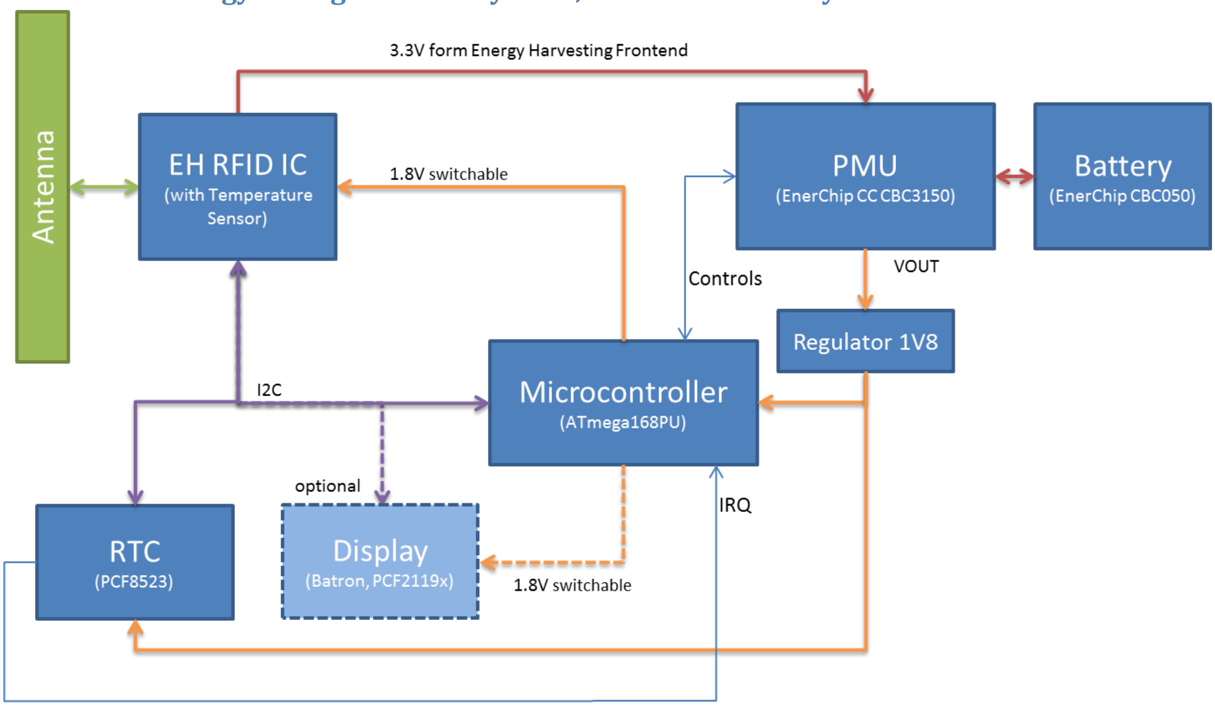


Figure 51: Block Diagram, PMU=CBC3150, Battery=CBC050

The disadvantage of this design, compared to variant 1, is that it requires an external voltage regulator because the PMU does not include one. For ultra-low power applications special voltage regulators are required. Typically the quiescent current of standard voltage regulators is in the range of 10µA to 100µA. Care has to be taken during selection. It is recommended to use Texas Instruments TPS780300250 which offers a quiescent current around 500 nA.

6.7.3 Variant 3 – Energy Storage Device: Seiko Ultra-Capacitor

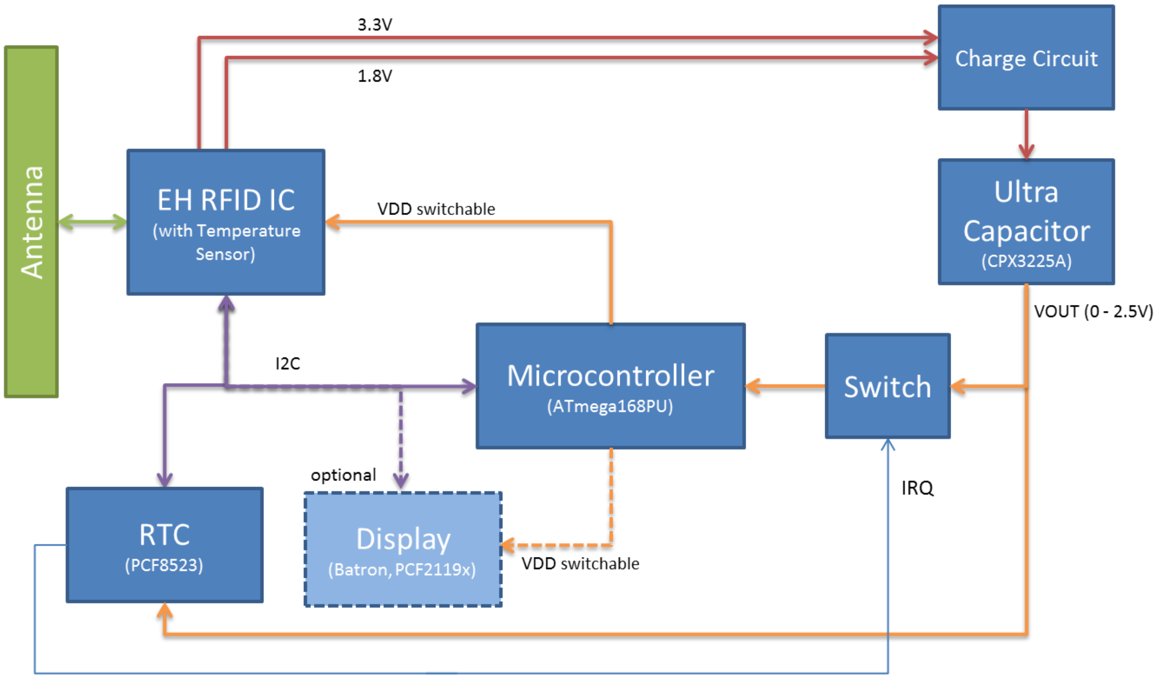


Figure 52: Block Diagram, Energy Storage Ultra Capacitor

This architecture uses a different approach. Instead of using a battery, an ultra-low leakage capacitor is used to store the energy. A switch is used to power up the whole system only when an action is required. This solution does not use a voltage regulator because it is not necessarily required. Additionally the current required for the regulator voltage can be saved.

7. Prototype: Temperature Logger

The reason for introducing temperature loggers in logistic applications is to guarantee that the cool chain is never interrupted during the delivery process. The advantage of the prototype which is developed in this work is that the battery can be charged wirelessly using the RF field from an RFID reader device. Communication and read out of the temperature logger can be done very easily using the often existing UHF RFID infrastructure.

A Temperature Logger for logistic applications should be capable to monitor the temperature of the product over 2-3 days. For some cases a battery lifetime of 1 week is desirable.

The timing measurement should be accurate enough that the worst case deviation over 3 days is only a couple of minutes.

Requirements:

- Real Time Clock
- Temperature Sensor
- Memory to store temperature readings
- RFID communication (Protocol: EPC-Gen2)

Example Use Case:

In the production of frozen or cool chain products this temperature logger is attached to the products package or to a carton of many products at the end of the production line.

After attaching the logger, which is also an RFID tag, it is initialized using UHF RFID EPC Gen 2 communication protocol. During the initialization phase the temperature logger is programmed with product information. Additionally the logging interval (sample rate) and current time have to be synchronized.

During the delivery process the logger measures the temperature of the goods/ware and stores these readings in the RFID IC’s user memory.

At the destination the RFID IC’s user memory is read out and the data set is analyzed for not allowed temperature values. If temperature readings are out of the valid area, the product is rejected. The temperature chart and the exact delivery time can be determined from the data set and can be used for quality control or statistical analysis.

After usage the temperature logger is put into a container or storage box where it is reinitialized and recharged. The recharging process can be done wirelessly without the use of any cables. To do this the radiated RF field from an RFID reader is enough.

During the whole delivery process the temperature logger runs from battery power. To further increase the operating time the logger can be supplied with an RF field. As soon as the received power exceeds the threshold level the temperature logger starts the recharging process.

7.1 System Architecture

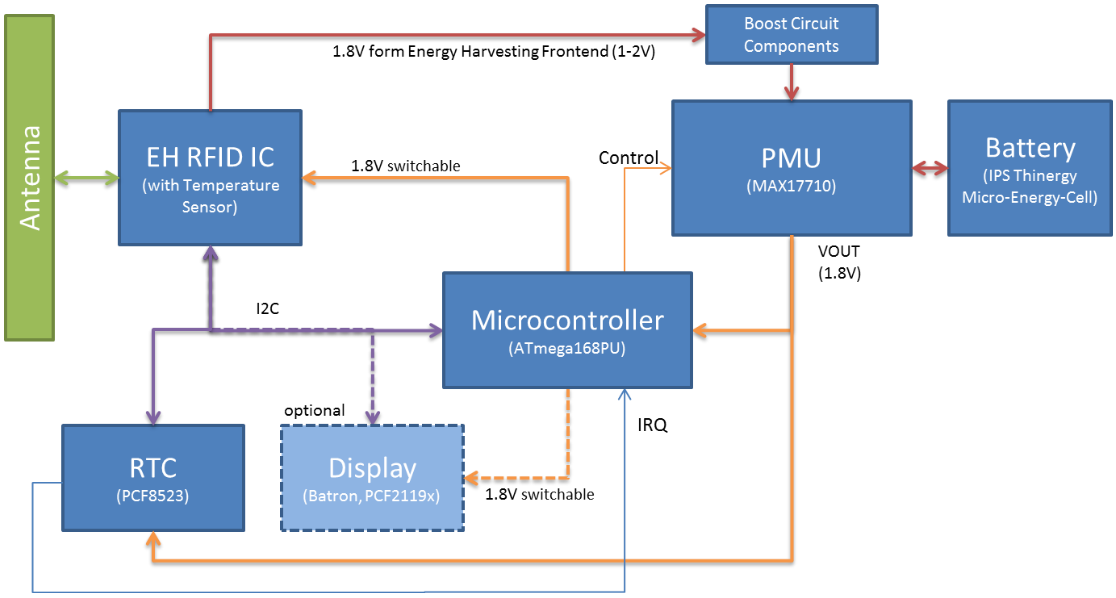


Figure 53: Temperature Logger Prototype - System Architecture

In Figure 53 it can be seen that the system consists of 5 major components. These components are a RFID IC with an energy harvesting frontend and a temperature sensor, power management unit, rechargeable Li-Ion battery, microcontroller and real time clock. As an optional component a display can be assembled (debugging).

Functional Description:

RF power is received from the antenna rectified and boosted to a higher voltage level in the EH RFID IC. This voltage is available on an output pin of the RFID IC. Because the output voltage is still not high enough for battery charging it requires an additional boost converter. The second boost converter is part of the power management unit. The power management unit has the appropriate circuitry which controls the charging process and does battery under-voltage protection as well. The most important requirement to the power management unit is its ultra-low power features, because the amount of power received from the antenna is very little. The microcontroller and the real time clock are powered permanently but the microcontroller has to spend most time in its deep power down mode to save energy. Another power saving feature is that the microcontroller can switch the power supply for the RFID IC's I²C interface and for the Display on or off.

For the digital communication the RFIC IC, the RTC and the display are connected to the microcontroller using the I²C Bus.

The real time clock's alarm and timer feature can wake up the microcontroller from its deep power down using an interrupt (wake-up) signal. Also there are control lines from the microcontroller to the power management unit which can put the PMUs voltage regulator into different modes for further power savings.

7.1.1 RFID and RF Energy Harvesting IC

For simplicity and size both RF frontends of the IC are connected in parallel to the dipole antenna.

To access the memory of the RFID for the MCU the I^2C interface is used. It has to be mentioned that RFID IC's wired interface is only powered during the I^2C communication. If the IC is accessed over the RF interface (wireless) EPC Gen2 Protocol this power supply is not required. In this case the RFID IC works like a passive RFID which is powered from RF energy of the reader.

For battery recharging the 1.8 V or the 3.3 V output pin can be used. But it is recommended to use the 1.8 V output pin because it offers better efficiency. The boost converter for charging the battery is required anyway.

7.1.2 Power Management Unit

The PMU is used in this case to boost the available input voltage to a level at which the battery can be charged. Secondly the PMU has to control the charging and discharging process of the battery. And thirdly the selected PMU does the output voltage regulation as well. This leads to a very simple design with lower part count.

In the schematic it can be seen that some additional external components are required to operate the built in boost converter.

7.1.3 Battery

For this application the Micro Energy Cell MEC from Infinite Power Solution is chosen because of its small self-discharge rate and its mechanical dimensions. Besides the other electrical parameters of this battery are very well.

7.1.4 Real Time Clock

The real time clock form PCF8523 is selected because it requires only a very little current (typically 150 nA) during its operation. The I^2C interface and a configurable output pin with alarm and timer functions are required additionally. The output pin of the RTC is used as a wake-up signal for the microcontroller when powered down.

7.1.5 Microcontroller

An Atmel AVR ATmega8PA (picoPower) was used because the development environment (Debugging Interface) for this controller was available. Furthermore the current consumption of this microcontroller is very low. The processing power this MCU offers is more than required. Another reason for choosing this controller was that it offers most state of the art power saving techniques which can be easily adapted to other microcontroller architectures.

Operating Voltage Selection:

Selecting the operating voltage of the system is an important parameter which influences the energy efficiency the system tremendously. For this application the operation voltage is selected as low as possible. For further details on choosing the clock frequency and operation voltage reference is made to microcontroller's data sheet.

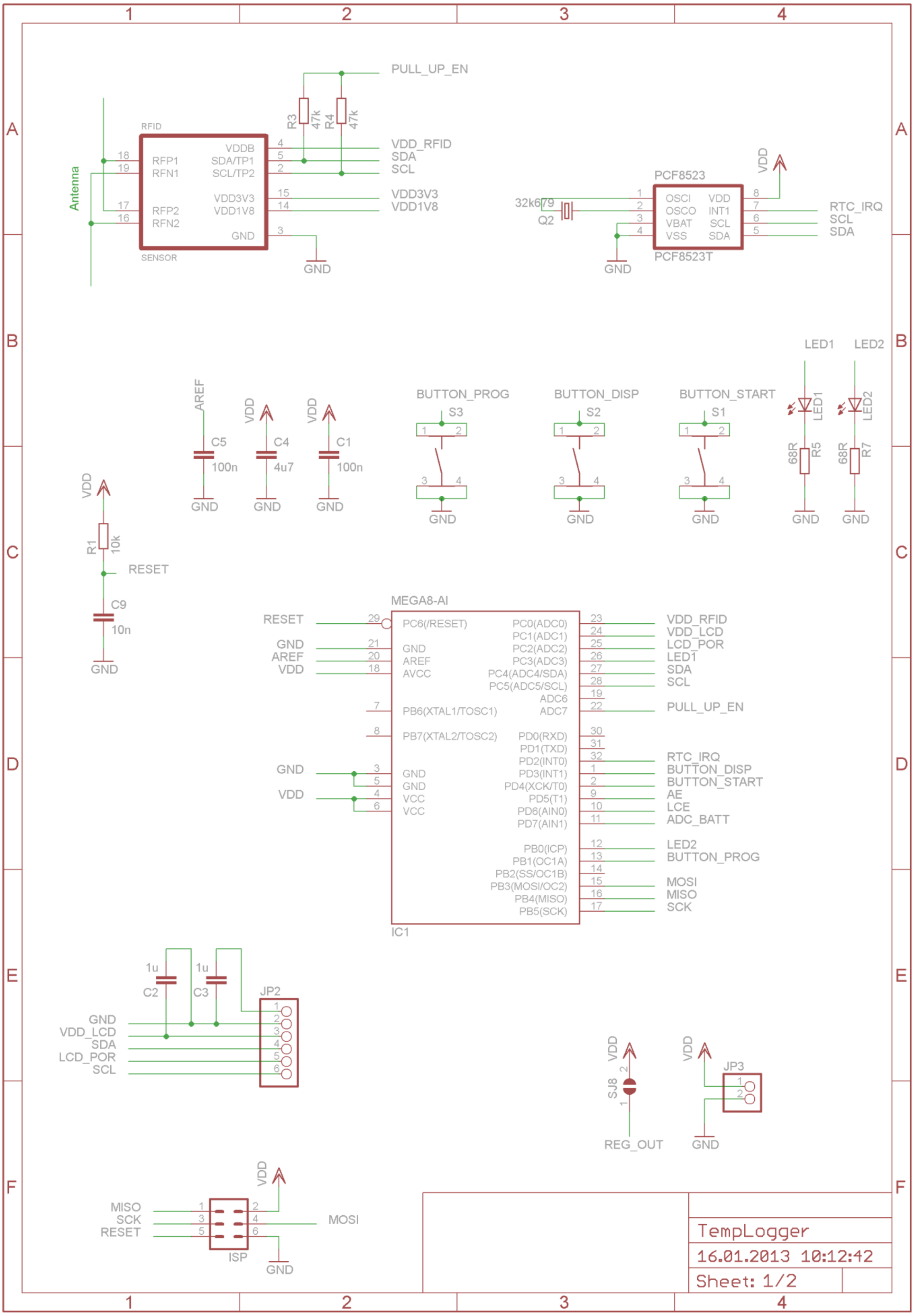
For power saving and simplicity reasons the internal RC oscillator of the microcontroller is used. Further it allows pre-scaling the clock frequency during runtime.

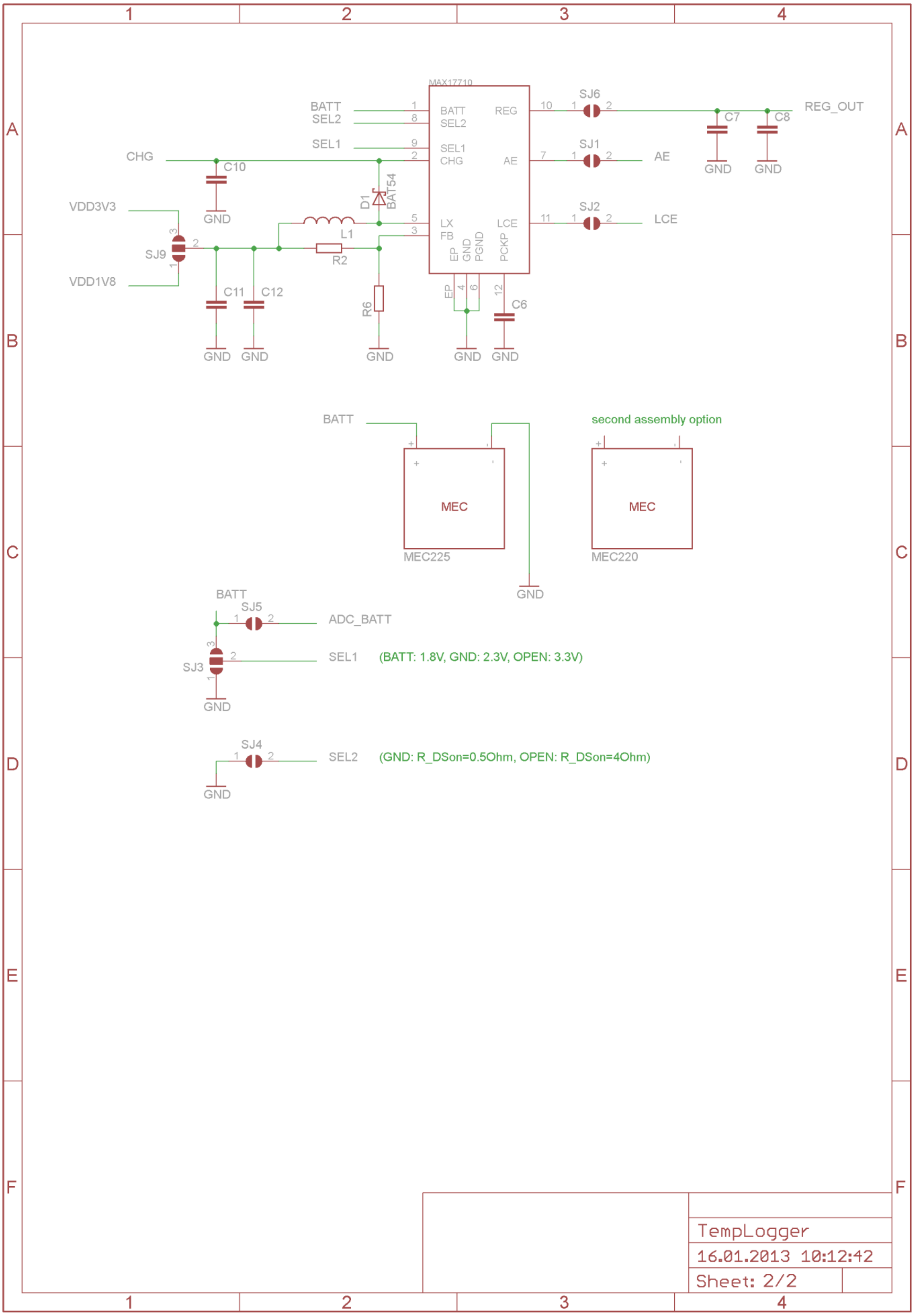
7.1.6 Display

BARTON LCD is mainly introduced for debug and demonstration purposes. It is connected to the I²C Interface. The display's V_{DD} line is connected directly to the microcontroller from where it can be switched on and off to save power.

Note: It is also used to indicate the state of the temperature logging device.

7.2 Schematic





For this design it was tried to keep the part count as low as possible. And it was tried to use as many of the ICs internal functional modules as possible.

7.2.1 Dimensioning of the MAX 17710's Boost Converter

The Energy-Harvesting Charger and Protector IC (MAX17710) includes a simple boost converter to support energy harvesting from low-voltage sources. The boost regulator can deal with power levels down to approximately 1 µW when operating in pulsed harvest mode.

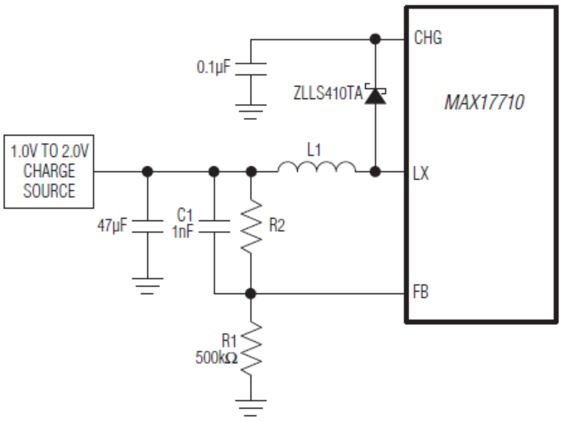


Figure 54: MAX17710 with Boost Circuitry for Charge Sources Between 1V and 2V, Image Source: [15]

CHG Capacitor

As recommended in the data sheet a capacitor with 0.1 µF should be connected between the CHG Pin and GND to attain highest charge efficiency. [15]

Boost Diode

A high speed diode must be selected to ensure that the diode turns on quickly and clamps the voltage rise at 6V of the LX Pin. It is possible to damage the LX pin if the voltage exceeds the maximum allowed value. As proposed the ZLLS410TA is chosen for this application. [15]

Harvest Source Capacitor

The data sheet describes that the harvest source capacitor should be a minimum of 70 times larger than the capacitor connected to the CHG pin. This minimum size ensures that the voltage can be boosted to the maximum charge voltage also under worse case conditions and ensures proper operation of the boost converter. [15]

$$W_{C_{Source}} = \frac{1}{2} \cdot C_{Source} \cdot V_{Source}^2 = W_{C_{CHG}} = \frac{1}{2} \cdot C_{CHG} \cdot V_{CHG}^2$$

$$W \ldots Energy$$
$$C \ldots Capacity$$
$$V \ldots Voltage$$

This leads to the equation to calculate the minimum required ratio between the source capacitor and the CHG capacitor.

$$Source\ Capacitor = \frac{4.125\ V^2}{0.485\ V^2} \cdot\ CHG\ Capacitor = \frac{4.125\ V^2}{0.485\ V^2} \cdot 0.1\ \mu F = 7.234\ \mu F$$

Increasing the size of this capacitor beyond this level improves the efficiency of the boost converter for low input power levels (<10µW). However the capacitor should not be chosen too large because the capacitor's leakage current influences the efficiency as well.
In the datasheet a maximum capacitor size of 47µF is recommended. For applications with very low power and low voltage sources it is recommended to use 0.1µF. [15]

Feedback Divider

Input voltage levels between 1.0V and 1.5V require boosting to charge the battery, but are too high to control the boost converters circuit efficiently. A voltage-divider reduces the voltage level on the Feed Back (FB) pin.

The following equations show how to calculate the component values for the voltage-divider as it is described in the IC's data sheet.

$$V_{Harvest-OFF} = V_{Harvest-ON} - \left(V_{FB_{ON}} - V_{FB_{OFF}}\right) = V_{Harvest-ON} - 0.5\,V\ (typ)$$
$$= 1.5\,V - 0.5\,V = 1.0\,V$$

$$R_2 = (V_{Harvest-ON} - 1.0\,V) \cdot 500\,k\Omega = (1.5\ \mathrm{V} - 1.0\ \mathrm{V}) \cdot 500\ \mathrm{k\Omega} = 250\ \mathrm{k\Omega}$$

$$V_{Harvest-ON} = V_{FB_{ON}} \cdot \frac{R_1 + R_2}{R_1} = 0.75\,V(typ) \cdot \frac{250\,k\Omega + 500\,k\Omega}{500\ \mathrm{k\Omega}} = \ 1.125\ \mathrm{V}$$

V ... Voltage

R ... Resistance

LX Inductor

The LX inductor is required for the boost converter's circuitry. The data sheet describes that a minimum inductance of 0.68µH is required to not exceed the maximum current rating of the LX pin. [15]

$$v = L\frac{di}{dt} \ldots relationship\ between\ self\ inductance\ in\ H, voltage\ and\ current$$

$$v, V\ \ldots Voltage$$
$$i, I\ \ldots Current$$
$$L\ \ldots Inductance$$
$$t\ \ldots Time$$

The lower equation is used to calculate the minimum inductors size. This ensures that the maximum allowed current through the LX pins nMOS transistor is not exceeded. [15]

$$LX\ inductor = \frac{V_{Harvest-ON} \cdot t_{BOOST-ON}}{I_{LX_{MAX}}} = \frac{1.5\,V \cdot 850\,ns}{1A} = 1.275\ \mu H$$

7.3 Firmware

7.3.1 General

The firmware for the microcontroller (Atmel AVR) is written in the C programming language. As development environment for the firmware as well as for debugging the Atmel Studio 6.0 was used. As part of this work, device libraries for the RTC, Display and EH RFID IC are implemented. Because all these devices communicate via I²C bus, these libraries are set on top of an I²C library. This facilitates portability of source codes to other microcontroller architectures.

The I²C communication handling is based on the microcontroller's internal Two Wire Interface (TWI) module.

Extensive use of the power saving mode of the microcontroller is made to ensure maximum operating time. To wake up the microcontroller from power down mode an external interrupt signal as well as the Watch Dog Timer (WDT) was used. The WDT was used to replace queues (while-loops) that are required for hardware communication. For example to wait for write complete or wait until the temperature conversion is complete. Using this technique allows a tremendous power reduction during waits. These power saving results are shown in Figure 60.

7.3.2 Flow Charts

Measure and Save a Temperature Reading

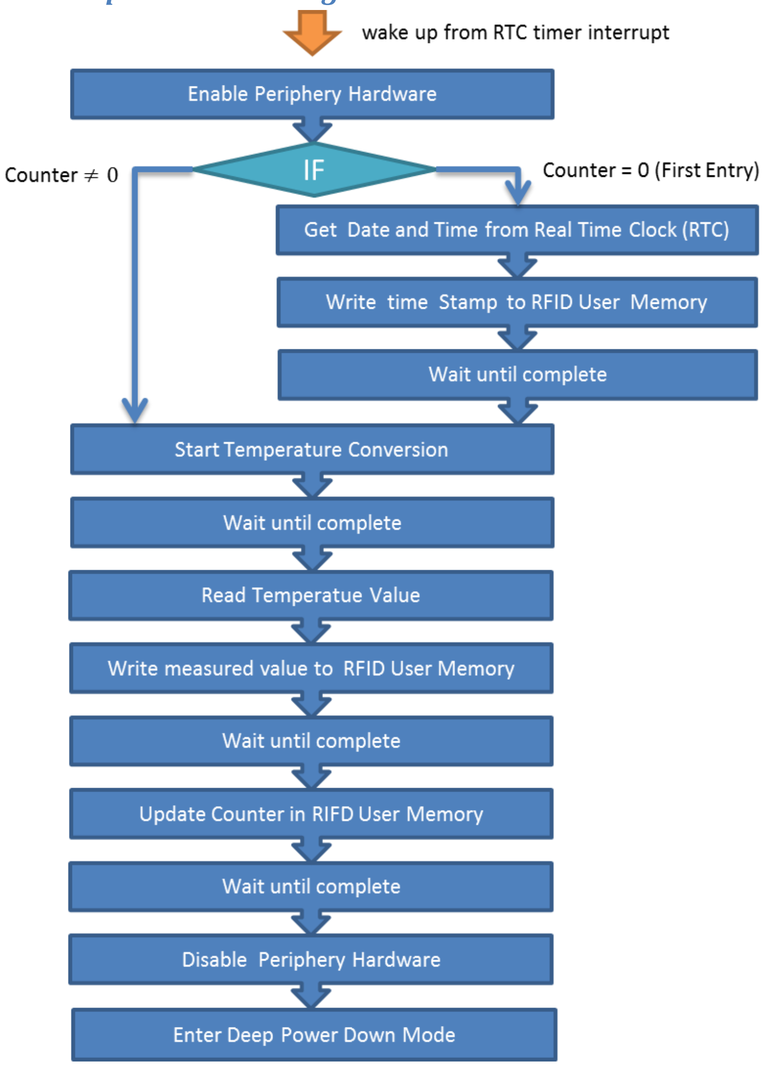


Figure 55: Microcontroller Firmware - Flow Chart - Measurement and Storage of one Reading

In Figure 55 the process of measuring one sample is described. The RTC's timer function is used to generate an external interrupt and wake up the microcontroller. After wake up the required periphery hardware is activated. If this is the first entry the microcontroller reads actual time and date from the RTC and writes this digital timestamp to the RFID IC's user memory and waits until this operation is complete.

Then the temperature conversion is triggered. Depending on the resolution mode this takes some time until the temperature measurement is complete. The measured temperature value is then read out and written to the first free memory space in the RFID IC user memory. After this writing process is complete the sample/measurement counter has to be updated.

Once the write operation is finished the microcontroller disables the periphery hardware and enters its deep power down mode.

Initialize Logger

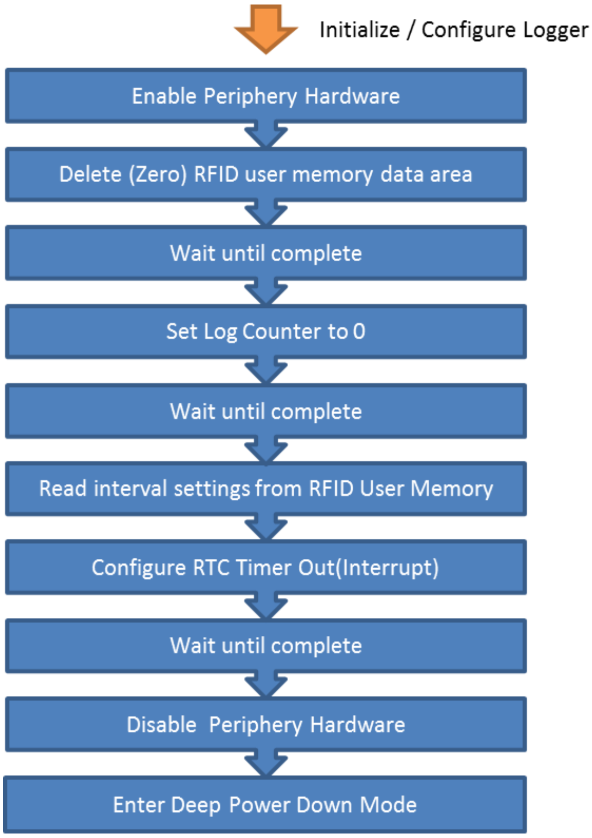


Figure 56: Microcontroller Firmware - Flow Chart - Logger Initialization

Figure 56 shows the initialization of the temperature logging process. This sequence is performed when the start button is pressed. By pressing this button an interrupt is generated. If the microcontroller is in power down mode it is woken up. After that the periphery hardware is enabled (RFID IC, Display if configured). The user memory area where the readings are stored is overwritten with zeros. Then the microcontroller has to wait until the write process is complete and resets (0) the log counter (measurement counter) afterwards. The log counter memory is placed in the RFID IC user memory so the microcontroller has to wait again until the write process is complete. After deleting the old data, the logger's configuration is read from RFID IC's user memory. The RTC timer is configured based on these settings. Now the RTC's output pin can wake up the microcontroller and trigger a temperature reading. After the RTC configuration is complete the periphery hardware is disabled and the microcontroller enters its deep power down mode.

Initialize RTC

Initializing the RTC is necessary when the system runs out of power or if the time is synchronized for more accuracy.

Precondition: The time stamp the user wants to program the RTC with has to be pre-calculated. Afterwards this time stamp has to be written to the configuration section in the RFID IC's user memory using a RFID reader device.

The microcontroller is woken up from the set time and date button as well as from an interrupt that is generated from the RFID IC. Tough the second option was not implemented yet. After wake up the microcontroller enables the periphery hardware and reads the time stamp from the RFID IC's user memory. Then this time stamp is converted into the RTC's required format. Afterwards the RTC is configured with these values. The microcontroller waits until the configuration is complete, disables the periphery hardware and enters the deep power down mode for power saving.

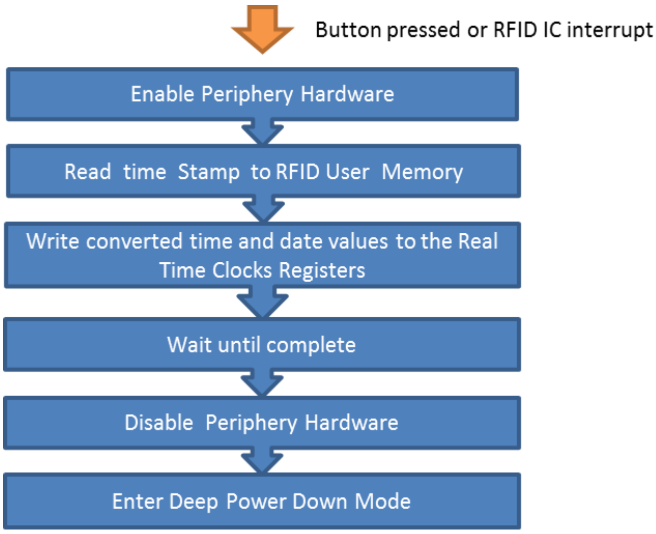


Figure 57: Microcontroller Firmware - Flow Chart - RTC set Time and Date

7.3.3 Memory Organization

The used EH RFID IC has a user memory size of 3328 bit ≙ 208 Words ≙ 416 Bytes. In Table 11 the memory organization is displayed in detail.

To save space, the time stamp is only saved for the first measurement sample. This can be done because the RTC guaranties exact timing.
For each temperature reading one word in the memory is used. This leads to a maximum capacity of 200 readings. The rest of the memory is used to store the device configuration and the time stamp.

User Memory Organization

EPC User Memory Address	I²C Memory Address	Description	Value (Range)
0	0x6000	Mode	0
	0x6001	Mode	0
1	0x6002	RFU	-
	0x6003	RFU	-
2	0x6004	RFU	-
	0x6005	RFU	-
3	0x6006	Logging Interval Seconds	0…255*
	0x6007	Logging interval Minutes	0…255*
4	0x6008	Hours	0…23
	0x6009	Minutes	0…59
5	0x600A	Seconds	0…59
	0x600B	Day	1…31
6	0x600C	Month	1...12
	0x600D	Year	0…99
7	0x600E	MSB (count)	
	0x600F	LSB (count)	count (number of temp measurements)

Table 11: Memory Configuration of the Logger Settings

*Note: The value used for interval (sec or minute) is the one that is not zero. Ranges 0...255, for seconds and minutes are allowed. If both values are not equal to zero then the second interval is chosen.

Address Blocks:

Address 0 (0x6000) – 3 (0x6007): Configuration
Address 4 (0x6008) – 7 (0x600F): Logging Status and Start Time Stamp
Address 8 (0x6010) – 207 (0x619F): Logging Data (Readings)

7.3.4 Power Optimization

The conversion time for the temperature measurement is strongly dependent on the chosen resolution mode. This time can be up to 75ms in maximum resolution mode. In Figure 58 the current consumption profile of the non-optimized system can be observed. After triggering the temperature measurement the microcontroller remains in active mode and frequently checks if the temperature conversion is complete. In Figure 59 this procedure is optimized. The microcontroller enters its power down mode immediately after triggering the temperature measurement and configuring the Watch Dog Timer (WDT) as a wake up source. This WDT is clocked from an ultra-low power and low frequency RC oscillator that allows an enormous power reduction. After the conversion time the WDT wakes up the microcontroller from power-down mode. The microcontroller checks if the conversion is successfully finished, gets the reading and writes it to the RFID IC’s user memory. Because writing the RFID’s user memory takes a few microseconds the microcontroller is put again into deep power-down mode and woken up from the WDT interrupt. The same procedure is executed again for the update of the log counter value.
The procedure steps described are also presented in Figure 55 however before power optimization.

Figure 58: Temperature Logger current consumption profile (before optimization)

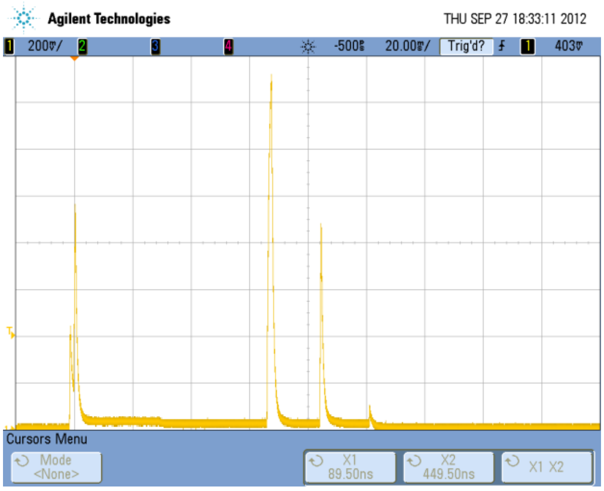


Figure 59: Temperature Logger current consumption profile (after optimization)

Duration: 78.4 ms
Energy Consumption: 365.6 µJ

Duration: 104.2 ms
Energy Consumption: 45.7 µJ
Energy Saving: 800 %

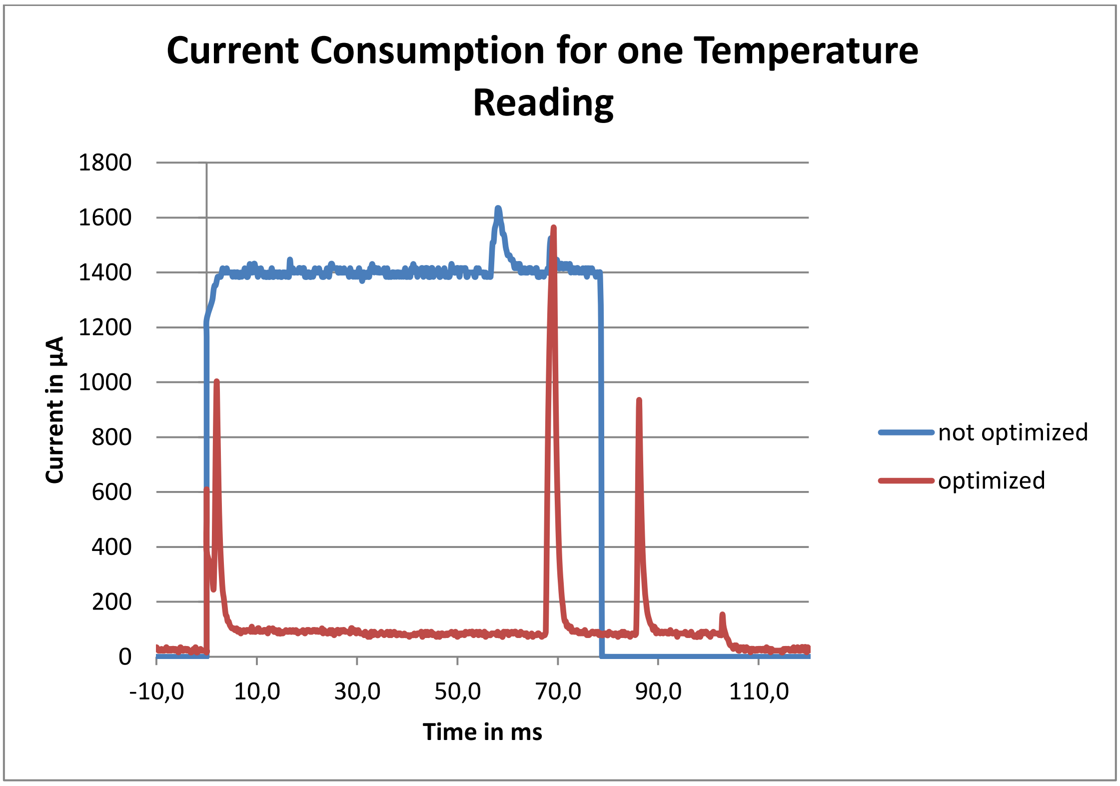


Figure 60: Comparison Current Consumption for one Temperature Reading

It has been shown that extensive use of the microcontroller power saving mode can decrease the energy consumption enormously. However there is an increase in the execution time because the WDT interrupts can only be configured in very rough timing steps. Additionally the execution time that is consumed due to wake-up and power-down increases the duration as well.

7.4 Prototype

7.4.1 Pictures

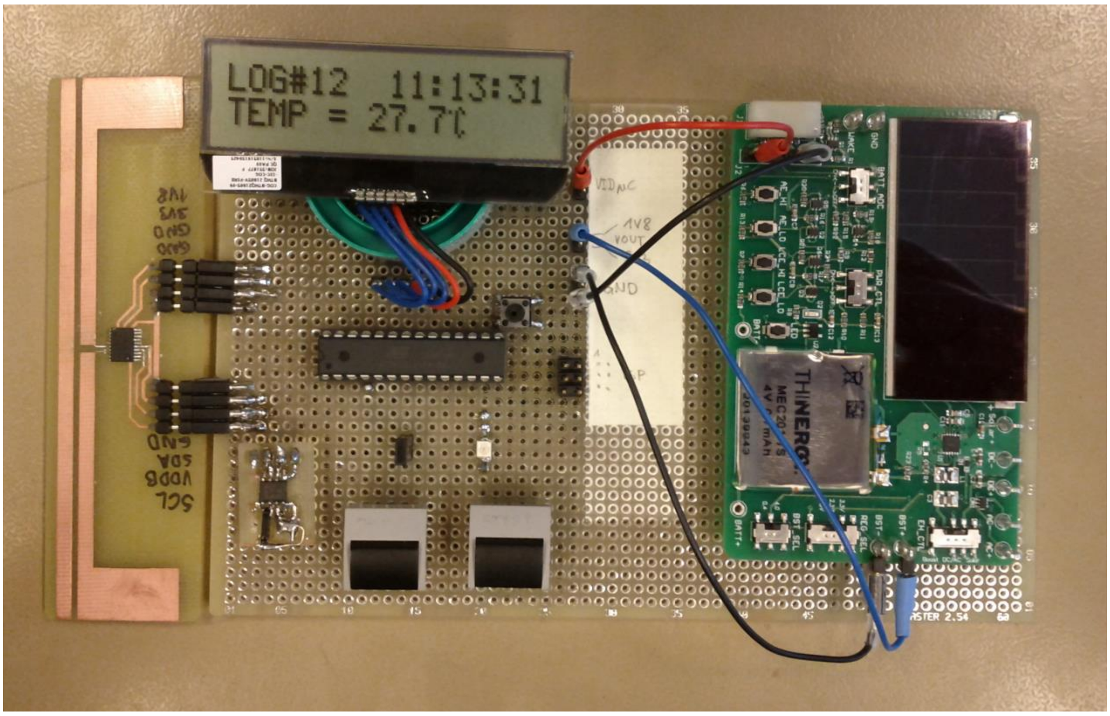


Figure 61: Temperature Logger Prototype with Debug Display and Power Management Unit

7.4.2 Layout

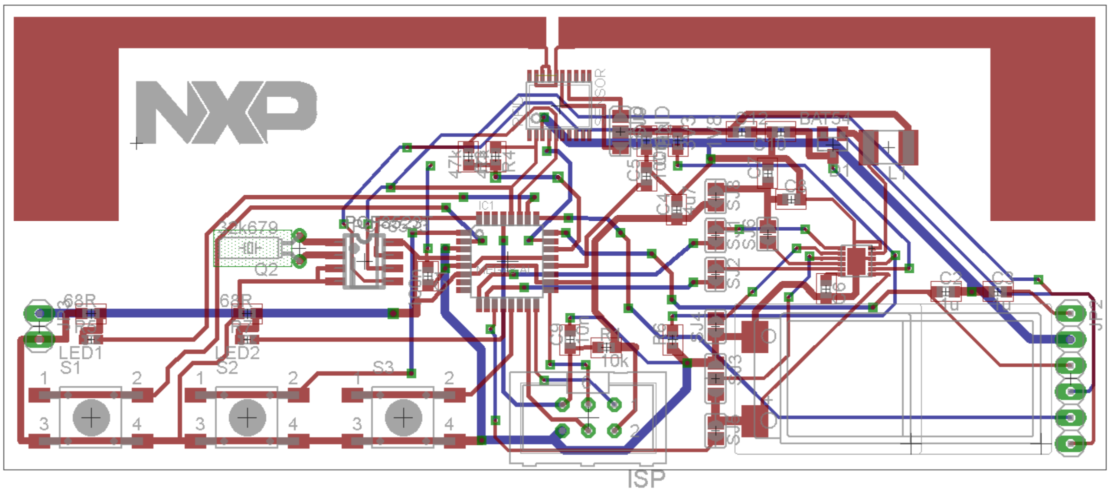


Figure 62: PCB Layout of the Temperature Logger

7.4.3 Usage

To use the presented temperature logger in the field it is required to know about the 3 major programming steps.

Set Time (program/initialize RTC):

1. Current time + 10 s → convert to the required time format
   Use the PC Software described in section 7.5 to execute this step.
2. Write timestamp & sampling rate to RFID tag's user memory
   Use the RFID reader's software to execute this step.
3. Press the "set time" button on the RFID temperature logger board to initialize RTC and complete this process.

Start Logging:

- Press the "start logging" button on the RFID temperature logger board

  This action starts the temperature logging process; the system erases the old logging data before and initializes the RTC timer interrupt for automatic wake up.

  The temperature logger stops its operation automatically as soon as the memory is full.

Readout:

Use the RFID reader's software to read the RFID tags user memory. Then copy this data and process it with the analysis tool (PC Software of section 7.5).

Note: Readouts can be done anytime, also if the logging process is still running.

7.4.4 Summary

This chapter has shown a working example concept for an energy harvesting temperature logger which can communicate and also can be charged wirelessly using UHF RFID technology.

Key facts:

- Battery Charge (dependent on assembly option):
  - Li-Ion Thin Film Battery with 130 µAh @ 3.7 V → ≈1.73 J
  - Li-Ion Thin Film Battery with 300 µAh @ 3.7 V → ≈4.00 J
- measuring one temperature sample requires:
  - ≈52 µJ
  - 33k/77k samples per battery charge (without quiescent power consumption)
- Quiescent current consumption
  - 1.7 µA
  - ≈76 h/176 h operating time per battery charge
- RFID memory size
  - 200 samples
- Recharging from RF power (RFID Reader)
  - ≈10 h (strongly dependent on input power)

It can be seen from the facts that the quiescent current consumption has a big impact on the operating time or the required battery capacity.

7.5 PC Software

For presentation purposes a software program was developed. This program converts the temperature readings coded in the format described in section 7.3.3 into a graph and a reading table with timestamps of each measured value (log file).

To guarantee maximum operability with most UHF RFID readers a manual solution for the user memory readout was chosen. Most software products delivered with RFID readers offer the opportunity to read the tags memory content using a graphical user interface. Then it is very simple to transfer data using copy and paste from one program to another.

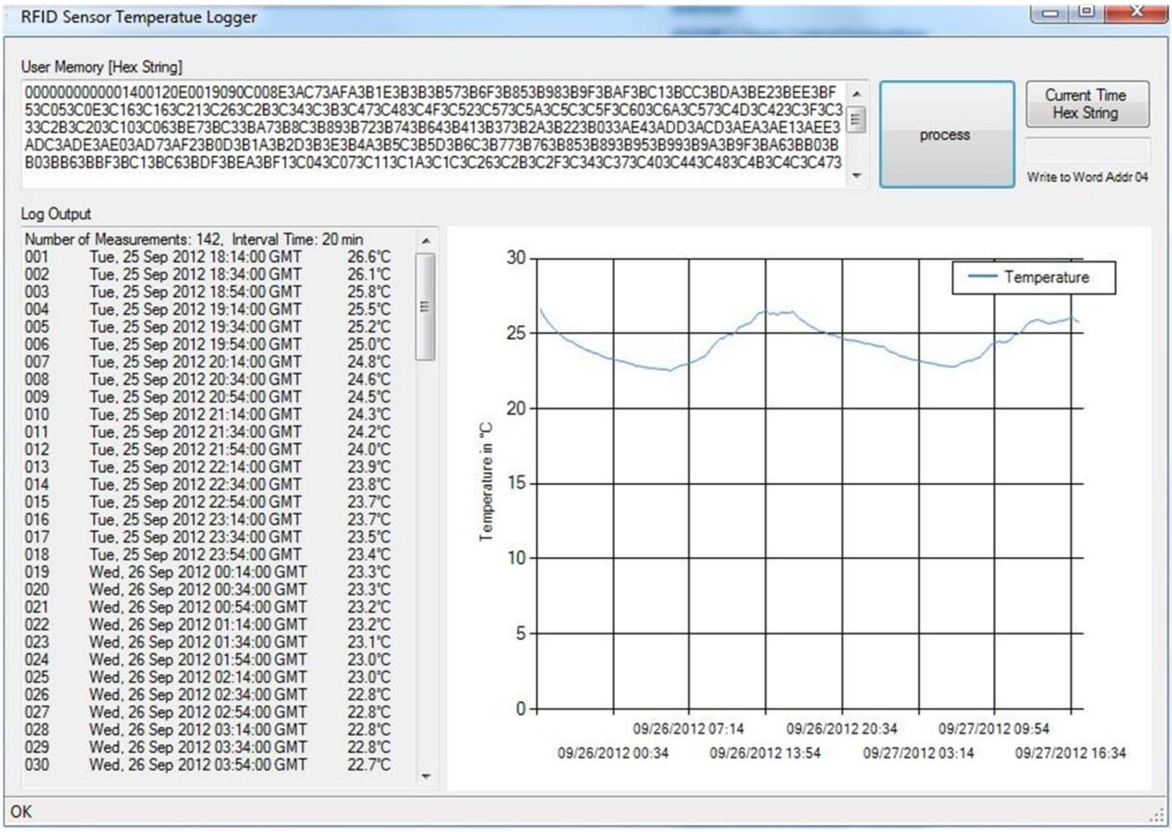


Figure 63: Screenshot of PC Software for Measurement Data Presentation

Figure 63: Screenshot of PC Software for Measurement Data Presentation shows the office’s temperature course over 2 days measured every 20 minutes.

7.6 Measurements

7.6.1 Static Power Consumption

To measure the static power consumption a source meter is used. This measurement device supplies the DUT and measures the drawn current very accurate.
With static power consumption the current or power that is required in the power down mode of the system is meant.

The readings for 1.8 V supply voltage in power down mode are 1.6 µA. This gives 2.88 µW.

The calculated current consumption based on the values of the devices data sheet should lead to only ≈0.65 µA. The reason for this difference is not clear. Measuring the power consumption of each IC on the prototypes board was not easily possible. It is also possible that a part of this current comes from the flux residue on the PCB.

7.6.2 Dynamic Power Consumption

For measuring the dynamic power consumption of the designed system a very simple current to voltage conversion circuit with an operational amplifier (op-amp) was used. The supply current for the DUT generates a voltage drop on a shut resistor. This voltage is amplified with a precision op-amp. The output signal of this op-amp is connected to an oscilloscope where the current consumption profile can be made visible. The amplification is set in the manner that current flow of 1 µA represents a voltage level of one 1 mV on the oscilloscope.

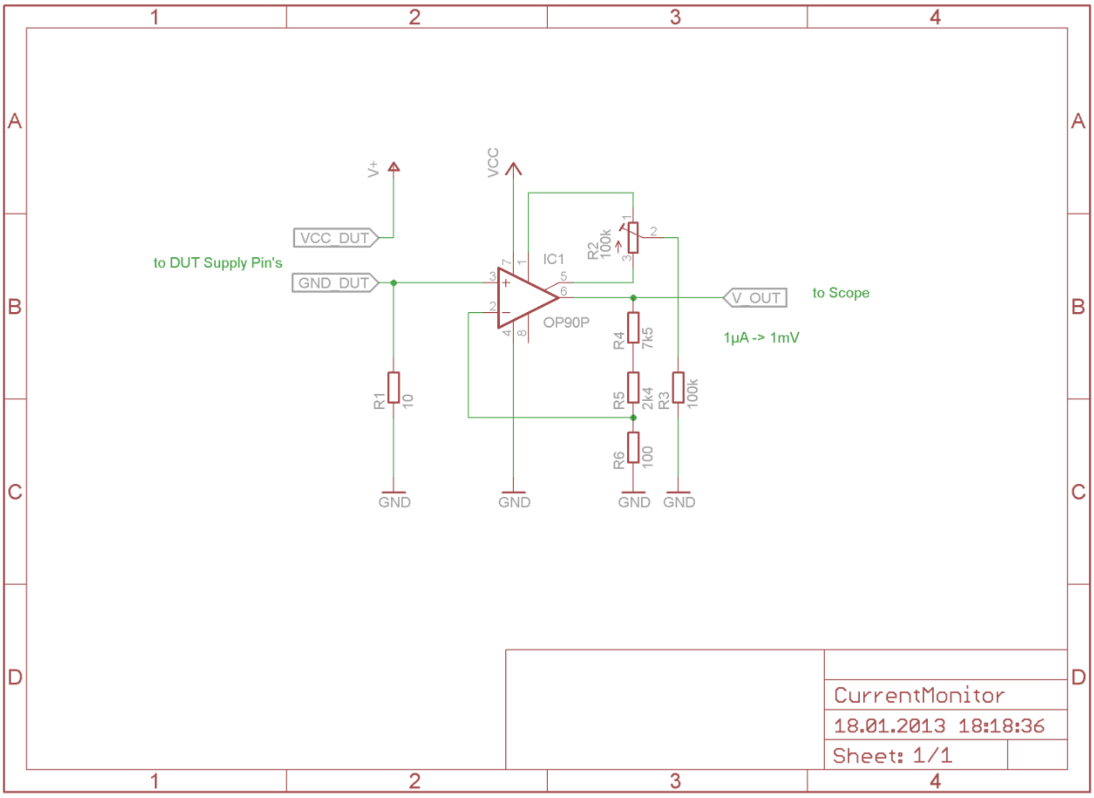


Figure 64: Schematic of the Current Monitor

7.7 Conclusion and Outlook

7.7.1 Lessons Learned

During the research it has been found that most of the system components (e.g. batteries, super-capacitors, voltage-regulators, and power management units) are often designed for mobile phones or other mobile devices. These devices have comparable huge battery capacities (1000…10000 times larger). In simple words their low-power requirements are not as hard as for this kind of application. Therefore special care has been taken during the component selection for the developed prototype.

It has been found that key parameters for optimizing the current consumption are clock frequency and operating voltage (in active mode) and quiescent currents (in power down mode).

It has been found that a proper test and develop environment which allows current, power and energy measurements of the designed electronic system are of great benefit. As part of this only a very simple circuitry to measure the current consumption dynamically was developed. Some manufactures of low power MCUs offer “Integrated Development Environment” (Software + Hardware) that allows quicker and easier development. Even a correlation between program code execution and current consumption is sometimes possible. This feature makes it much easier to find code locations that cause high current consumption or delay the execution.

7.7.2 Further Improvements, Optimization Steps

Further reduction of the power consumption, especially reducing the quiescent current would increase the systems operation time. The current consumption of the microcontroller in active and power down mode is not as low as mentioned on the data sheet. Also the current drawn from the real time clock is larger than expected. Further debugging is required to find the cause.

A function which could be additionally implemented is the interrupt notification from the EH RFID IC. It can generate an interrupt signal when new data are written to the tag. This would allow updating the real time clock, initiated by the RFID reader device.

7.7.3 Outlook

The temperature logger is only one example; of course the developed system can be extended with other types of sensors (e.g. humidity, light, vibration, pH-Value, gas concentration …). These sensors could be interfaced using the analog to digital converter (ADC) of the microcontroller.

8. Conclusion

One of the most significant results of this thesis is a more detailed knowledge about the system requirements for RF and Ultra-Low Power Energy Harvesting Systems.

Radio Regulations

Great attention should be given to radio regulations when investigating new business cases. There are a lot of differences in radio regulation over the world. Some regulations only allow transmit duty cycles of 10% which tremendously reduces the amount of power that can be harvested. Also the listen before talk requirement can decrease the effectiveness.

Energy Storage Device

One of frequently asked questions was if it is possible to replace batteries with capacitors. Since batteries are large, expensive and not reliable under extreme operating conditions. The answer to this is that the leakage current of currently available ultra-capacitors is too high to overcome long power outages. Also a lot of energy has to be charged into the capacitor that can't be used afterward without additional conversion hardware. Modern batteries instead offer very little self-discharge rates. This implies that they can hold their charge a long period of time with only little losses. The drawback of battery technology is its fixed cell voltage. This demands a voltage boost conversion for charging in most cases. Furthermore a battery protection circuitry is required. These make a battery management system even more complex.

Energy Harvesting RFID IC

One of the main insights is that a passive RFID frontend, that is highly optimized for maximum read range, doesn't fulfill the requirements of high power output well. The results show that the RF harvesting system is designed toward high sensitivity. The circuitry that prevents the device from destroying itself in high field strength inhibits the system from delivering higher output power in the case of energy harvesting.

The comparison between SPI and I²C interface shows that power saving during communication can be achieved if using SPI instead of I²C. The power savings are mainly caused by higher transfer rates. Nevertheless the pull-up resistors for the I²C bus lines contribute. But beside the power consumption I²C or one wire interfaces have advantages in their low pin count.

Optimization Target

The focus of this thesis was not set on optimization of the RF energy harvesting transducer furthermore the system level optimization was the important.
One of the key findings of this thesis is the decision whether the system should be optimized for low power or low energy consumption. It is important to make this decision early in the design process because it has large influence on the selection of the components. Therefore many factors have to be considered to make a sound decision.
The most important factors are:

- Availability of the energy source (energy harvesting source)
- Size of the power source
- Operating time and power consumption profile of the system

Low Power or Low Energy requirement lead to different system concepts and different requirements on the system components. Dependent on the claimed operation time of the EH system, two major groups with different requirements can be formed as follows:

Low Energy optimization:

- Quiescent current of the used IC's is the main concern
- Leakage current of the energy storage can be a limiting factor
- Efficiency of the components is important
- Run external interfaces like I^2C, SPI, UART at highest speed to reduce the MCU's active time

Low Power optimization:

- Lowest possible power consumption
- Exchange execution time with power consumption if possible
- Capacity of energy storage as small as possible to ensure fast startup

9. Outlook

9.1 Remaining Work

Effect of Auto-tuning

Due to the reason that a variable load on the power output of the energy harvester influences its input impedance, a static antenna matching is not very efficient. An automatic tuning system which does peak power point tracking could help to improve the overall efficiency of RF energy harvesting system. A detailed analysis is required to prove if costs in power consumption and chip size for the automatic tuning system can counterbalance its benefit.

Backscattered Signal

A very important factor for communication of passive UHF RFID is the strength of the backscatter signal or also called radar scattering cross-section (RCS). The variable load connected to EH RFID tag's output effects it input impedance. This can affect the strength of the modulation signal (RCS). To ensure proper operation of the EH RFID IC under all operating and load conditions a details analysis would be required.

Antenna Design

A suitable antenna for the intended use has great impact on the systems overall performance. Many requirements affect the design and shape of an antenna. Some of these requirements are: Form Factor, Anisotropy, Influence of objects close to the antenna (e.g. attached electronic Circuitry), Cost and many more.

Broadband Energy Harvesting

Another idea that's worth further investigation is to not only use the power available at a single frequency but adding up the power available from a larger frequency spectrum (Broadband or Multiple Frequencies). This can significantly improve the power output and availability.

9.2 Reduction of Electronics Power Consumption

The properties (quality, efficiency) of energy harvesting passive smart devices are strongly dependent on semiconductor technology. Also improvement in battery or storage capacitor technology has an influence.

Assumed that the regulations for radio transmissions don't change the physically available RF power budget for UHF RFID doesn't change either. Only improvements in the RF to DC conversion circuitry influence, over its efficiency, the power budget that is available for the electronic system of the smart device. Of course improvements in the antenna design have influence too, but not on IC level.

More efficient semiconductor technology can increase the functionality of the system of the smart device as well as other properties like communication range or operating time due to a reduction of the energy consumption.

[1] showed in their work that battery technology only has made a slight progress in its development in the past. They showed that battery capacity has increased only about 20% in the last 10 Years.

In contrast to that [21] showed that also the efficiency of computing changes almost with the same speed that Moore's law predict. It is shown that the electrical efficiency of computing doubles roughly every year and a half. [21]

These predicted improvements will enable new use cases and innovations for smart devices and wireless sensors. This means that they will become smaller, smarter, last longer and offer more performance than nowadays.

10. Summary

The central topic of this paper deals with wireless self-sufficient systems namely smart passive devices, its use cases and its implementation. The main fields of applications for micro energy harvesting are wireless sensors and actuators. The advantage of these energy harvesting systems is that they are maintenance free (no manual recharging or battery replacement is required). Various energy harvesting techniques (solar, vibration, thermal and RF energy) are analyzed and compared to each other. The result shows that solar cells offer the highest power output per area compared to the other techniques. The power outputs from vibration, thermal or RF energy harvesters are comparable low, additionally a signal conditioning is required in most cases to supply electronic systems. However this thesis is focused on RF (UHF) energy harvesting because a RFID test chip with a wired interface and an energy output is the central topic of this work. Its characteristics are analyzed as part of this work. This RFID tag does RF to DC conversion and allows wireless communication with a reader device at the same time. The main advantage of this RFID based solution is that power and information are transported using the same medium, which makes this system very cost effective. Use cases for this technology are e.g. wireless updateable displays (battery less) or temperature loggers to monitor the cold chain during distribution.

To develop a prototype the available power or link budget has to be determined first. For this purpose a test setup and software was developed to measure the power output as well as the efficiency of the IC. Also the input impedance of the RF frontends can be measured for antenna optimization. Furthermore a part of this test setup was used to analyze the link budget with attached antennas. Two different antenna designs are compared to each other.
Based on the determined link budget a research for suitable components was started. Due to the very tough power/energy requirements the choices were not very large. The target to develop a wireless self-sufficient display was overruled because displays that meet the power requirements were not purchasable at the required time. Which lead to the decision to develop a wireless rechargeable temperature logger instead. Based on different electronic components multiple design architectures are proposed.

A prototype was developed to prove the concept. The main work was the development of an energy optimized firmware for the microcontroller. Software Libraries to control the RFID IC, real time clock and display had to be created. After getting the system running the power consumption was measured and optimized. Many power saving techniques are used to bring the current consumption down. Besides the extensive use of the power down modes, dynamic clock scaling, and a low frequency RC oscillator are used.

It has been shown that the prototype can run multiple days from its tiny rechargeable battery. Also wireless charging of this battery is possible.

The measurement results show that the biggest limitation for the temperature logger prototype is its drawn quiescent current.

The thesis showed that RF energy harvesting works for RFID applications because the transmitter is close to the receiver. However the power/energy requirements to the electronic system are very challenging.

Appendix

mPicoSys Smart Display Demonstrator

The company mPicoSys developed in cooperation with NXP Semiconductors a smart e-paper display that is only powered from an RF field and can be updated using UHF RFID technology (EPC Gen2 Protocol).

mPicoSys has the know-how to design ultra-low power e-paper display controllers. These controllers can deal with very little supply currents. Typically e-paper displays have the property to draw high current during the update phase.

As mentioned before this system is only powered from an RFID Readers RF field and can reach update ranges up to 55 cm in front of a small patch antenna (+2 dBi) powered with +25 dBm.

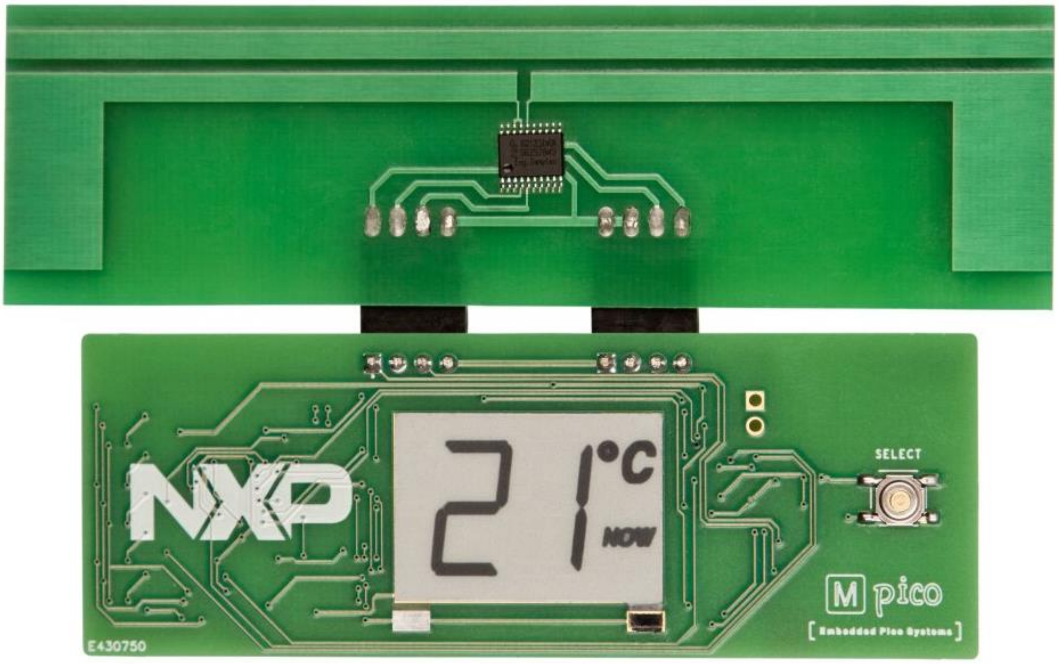


Figure 65: mPicoSys & NXP RFID e-Paper Display Demonstrator, Image Source: mPicoSys

Functionality:

The demonstrator starts updating automatically when receiving enough power.

- Temperature Display (min, max, now)
- Price Tag
- Lap Counter

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